Fall 2012

SOCIAL SCIENCES AND ENGINEERING PRACTICE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING
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The
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The BRIDGE

LINKING ENGINEERING AND SOCIETY

Editor's Note

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NAE News and Notes

Editor's Note

Daniel Metlay

How Social Science Informs Engineering Practice

If one stepped back and viewed the state of technological development in the United States since the end of World War II (although the demarcation is hardly precise), it would appear dramatically different from that of earlier years. Technological capacity, driven by scientific research and engineering practice, has exploded in ways that could not have been predicted or anticipated in 1945. Consider the technology-driven revolutions in telecommunications, access to information, and agriculture that have significantly altered the lives of the last two generations.

Concurrently, the relationship between technology and society began to change fundamentally. Where once choices among technological alternatives were made by a narrow set of parties, either entrepreneurs or government officials, those decisions increasingly became subject to public scrutiny and influence. Where once the consequences of a technology were seen as largely localized, impacts came to be understood as more wide-ranging—geographically and temporally. Where once a particular technology could be assessed independently, its interaction with others now needed to be considered; for example, choices about new energy production technologies can affect transportation choices, housing patterns, and agricultural productivity.

By the mid-1970s, evidence had accumulated that, notwithstanding the general public's deep appreciation for technological development, strains of skepticism and discomfort were starting to emerge (LaPorte and Metlay, 1975a, 1975b). Controversies over the fluoridation of public water supplies, government support for building supersonic commercial aircraft, and the use of pesticides challenged how decisions were made about technological development and deployment, and prompted Langdon Winner's memorable question (Winner, 1980): Do artifacts have politics? Today there are few who would argue with the question's tacit affirmative answer.

As the relationship between technology and society grew more nuanced and multifaceted, social scientists became more intrigued by it. A relatively rich literature, and even new intellectual disciplines—such as risk analysis and the social study of science and technology—materialized. Drawing on three strands (among many) from that literature, this volume of *The Bridge* focuses on the question, "How can social science inform engineering practice?"

The first thread concerns increased complexity and whether it constrains the management of technological systems, with respect to either shaping relevant and appropriate public policies or governing the systems' operation. Daniel Sarewitz and I argue that certain societal problems, many of which are associated with advanced technologies, are so "messy" that standard and familiar decision strategies cannot adequately address them. Nick Pidgeon describes two perspectives for thinking about how organizations operate complex technical systems such as nuclear power plants and space shuttles. One view maintains that these organizations can be designed to be as reliable as needed, and the other, that "normal accidents" are inevitable.

The second thread looks at how the general public evaluates risky technologies. Roger Kasperson discusses the "social amplification of risk." He explains why events that seem to be of very minor importance to specialists can nonetheless evoke strong public reactions that have substantial consequences. Hank Jenkins-Smith and his colleagues explore public preferences for managing high-activity radioactive waste. This work may be helpful as national policymakers consider new initiatives in the wake of the Obama administration's decision to seek alternatives to the Yucca Mountain repository project.

The third thread uses the case-study methodology to investigate instances where the engineering and social dimensions were tightly coupled. Jameson Wetmore presents three examples when engineers and social scientists collaboratively worked on projects ranging from the regulation of nanosilver in antibacterial clothing to transmitting unspoken social cues to the blind to designing stoves for villagers in Ghana. He argues that without that collaboration the projects would not have succeeded. Ray Wassel summarizes a report by the National Academy of Engineering and the National Research Council that investigated the root causes of the Macondo well blowout. He touches on three issues: the interpretation of data associated with the cementing step; whether early warnings about the reliability of the blowout preventer were discounted; and why regulation by the Minerals Management Service was so lax.

Notwithstanding their varied approaches, all the articles, either explicitly or implicitly, address two key issues that are at the heart of the engineer's vocation: First, how are uncertainties resolved, perceived, communicated, and managed? Second, how are tradeoffs among salient values made? But, besides being of some intellectual interest, how might the two key issues inform engineering practice, which, after all, is the focus of this volume?

Some of the articles offer fairly straightforward prescriptions. In our analysis of messy problems Sarewitz and I argue that the current debate about climate change policies is misdirected and that misdirection is responsible for the public policy stalemate. Pidgeon reminds us that there may be constraints, imposed by the complexity of a technological system, that inherently limit an organization's ability to prevent accidents and upsets. These limits should be kept in mind when new systems are designed and implemented.

In the other articles, the recommendations are more implicit but do seem to follow rather directly from the analyses. Kasperson's explication of the social amplification of risk does more than reaffirm the maxim that "perceptions are reality." He cautions that engineers' calculations of risk are important, but by no means exhaustive, measures of how the general public actually responds to technological innovations. Finally, Wassel's description of what happened at the Macondo well leads one to ask, almost immediately, What if the deepwater oil exploration industry established an organization similar to the one created by the nuclear power industry (INPO) to monitor the performance of individual companies and disseminate best practices?

In sum, by exploring the management of uncertainty and the trading off of values from a multiplicity of perspectives, the articles cumulatively illustrate how social science can indeed inform engineering practice.

References

LaPorte, T., and D. Metlay. 1975a. Technology Observed: Attitudes of a Wary Public. Science 188: 121–127.

LaPorte, T., and D. Metlay. 1975b. Public Attitudes Toward Present and Future Technologies. Social Studies of Science 5: 373–398.

Winner, L. 1980. Do Artifacts Have Politics? Daedalus 109: 121–136.

Transition at *The Bridge*: A Farewell and a Welcome

Carol Arenberg

Cameron Fletcher

This issue marks a transition in the editorial office of *The Bridge*. Carol Arenberg, who has been managing editor of *The Bridge* and NAE Senior Editor since 2001, has decided to retire. Her successor is Cameron Fletcher. During the transition period, which included the editorial work-up for this issue, Carol and Cameron worked together to ensure a smooth transition, and I can testify that they have been successful!

Prior to her work with *The Bridge*, Carol was the editor for the National Research Council Commission on Engineering and Technical Systems (CETS) for five years. During her 11 years as managing editor, *The Bridge* has changed dramatically—from a small publication of interest mostly to NAE members to a widely respected periodical (in print and online) that reaches most members of Congress and relevant government agencies, university schools of engineering and libraries, and interested individuals across the United States and abroad. Carol worked closely with my predecessor, **George Bugliarello**, during his role as "Interim" Editor in Chief. As she approaches retirement, Carol looks forward to spending time with her three children and their spouses and her seven grandchildren, traveling (next up: Machu Picchu, Quito, and the Galapagos), and more hiking in the Rockies and Alps. She also plans to resume writing in her journal (and maybe a novel), taking some long-delayed courses at a local university, learning photography, and brushing up on her language skills in Russian and French. I have the sense that Carol will remain very busy during retirement!

Cameron comes to the NAE from the NRC Division on Earth and Life Studies, where she was Managing Editor of the quarterly *ILAR Journal*, and, before that, the Division on Engineering and Physical Sciences. During her 25 years with the National Academies, she has edited full-length committee reports, meeting and workshop summaries, and a host of other types of publications both online and in print, on subjects ranging from laboratory animal research to software engineering for defense systems to renewal of DOE infrastructure. Her editorial strengths include an eye for anomaly and ear for nuance, emphasis on clarity and concision, and bilingual fluency (English, French), conversational Spanish, and a smattering of other languages. Among her personal interests, she enjoys woodsy walks, dogs, travel, and dabbling in languages. She received her BA cum laude from Bryn Mawr College.

In the short time I have known Carol she has won my gratitude for the commitment, energy, and skill she has devoted to *The Bridge*. By the same token, I know that we will be in good hands going forward with Cameron as managing editor.

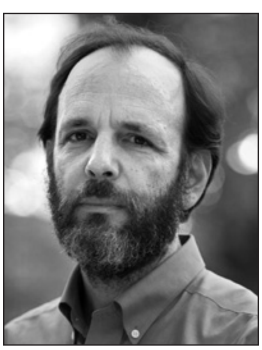
Ronald Latanision
Editor in Chief

Getting the politics of a messy situation right may make it easier to get the science right, too.

Decision Strategies for Addressing Complex, "Messy" Problems

Daniel Metlay and Daniel Sarewitz

Daniel Metlay



Daniel Sarewitz

More than a half-century ago, two social scientists, James D. Thompson and Arthur Tuden, advanced what has come to be called the "contingency theory" of decision making (Thompson and Tuden, 1959). They argued that there is a connection between two properties of problems—the degree of uncertainty and the extent of disagreement over trade-offs among important values—and the strategies appropriate for addressing those particular challenges. Although Thompson and Tuden developed a set of hypotheses about how different types of problems are solved, their theory is fundamentally normative: depending on the attributes of the problem at hand, some strategies are suitable for solving it and others are not.

One class of problems, termed messy, wicked, or ill-structured, is characterized by (1) a high degree of uncertainty about how options are linked to outcomes and (2) substantial controversy over trade-offs among values. Examples of messy problems include preventing the spread of nuclear weapons, regulating the production and use of chemicals, and reforming health

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[1] Affiliation is presented for identification purposes only. The views expressed in this paper are those of the authors and do not represent the views of the Nuclear Waste Technical Review Board.

care. Addressing such problems often requires a mix of scientific research and engineering practice, which, by necessity, must be undertaken in a context of political disagreement.

In this article, we begin with a brief discussion of the Thompson-Tuden contingency theory and a description of decision strategies for addressing well-structured problems. We then examine specific strategies that are appropriate, according to the theory, for tackling messy problems. We conclude by offering some general observations about disentangling messy challenges.

Decision Strategies for Addressing Well-Structured Problems

Programmed Decision Making

If the level of uncertainty inherent in a problem is low and there is a strong consensus on values, decisions can be computed, sometimes even programmed. In such cases, choices follow directly from pre-established rules. Familiar forms of this decision-making strategy include cost-benefit analyses and optimization methods, such as the methods used in operations research. Among the problems amenable to this strategy are determining a firm's tax liability or an individual's eligibility for welfare payments.

Although programmed decision making is always vulnerable to the criticism that it does not make allowances for exceptional or ambiguous cases or account for how (and by whom) costs and benefits are determined, this strategy is often sought by decision makers because it places great emphasis on efficiency.

Bargaining

If uncertainty is low but there are disagreements about trade-offs, bargaining is the appropriate decision-making strategy. Bargaining can be effective in such cases because the understanding about connections between options and outcomes is sufficient for decision makers to appreciate how different alternatives affect salient values.

Common examples of this strategy include logrolling by legislators, compromises in negotiations, and sensitivity testing in multi-attribute utility analyses. This strategy is also used in the writing of regulations, in deliberations on appropriations bills, and in adjusting Social Security payments to reflect inflation. Because value trade-offs are inherently subjective, the stability of a bargain is, perhaps, the best measure of its success.

Incremental, Adaptive, Stepwise, or Trial-and-Error Strategies

An incremental strategy, otherwise known as adaptive, stepwise, or trial-and-error decision making, is fitting for addressing problems characterized by substantial uncertainty and by a general consensus on values. Incremental strategies rely on a "cybernetic" feedback model (Steinbruner, 1974). A decision is made, and its impacts are closely monitored. When deviations from the desired (and agreed to) outcome are discovered, adjustments (typically "small") are made. This process is repeated until the desired outcome is reached. Of course, irreversible outcomes at any stage doom this strategy.

The effectiveness of an incremental approach depends on how well problem solvers can detect when actual outcomes deviate from the desired outcomes and how well they can find ways of making mid-course corrections. Consequently, the behavior of the problem solvers and their organizations is more important in this strategy than in programmed decision making or bargaining.

Messy problems are characterized by an incomplete understanding of how options are linked to outcomes and by conflicts over values.

Addressing Poorly Structured Problems

Messy, or poorly structured, problems are characterized by a very incomplete understanding of how options are linked to outcomes and by intense conflicts over values. In these situations, people are likely to disagree not only on what actions to take but also on what the results of those actions are likely to be and what constitutes progress.

These complex challenges are usually closely connected with other issues; are constrained by politics, economics, and ideology; have significant gaps in both information and understanding; and are resistant to change, even when evidence has shown that the status quo is untenable. In addition, the views of key actors about uncertainty and value trade-offs tend to be mutually exacerbating, that is, substantial uncertainty promotes conflicts over ends, and such conflicts, in turn, heighten awareness of the many sources of uncertainty.

Some Proposed Approaches for Dealing with Messy Problems

According to Thompson and Tuden, "inspiration" is the appropriate "strategy" for addressing demanding situations like the ones just described. They also acknowledge, however, that its success may depend largely on the emergence of a charismatic leader. In fact, almost as soon as they advance the strategy, Thompson and Tuden question its efficacy. "The most likely action in this situation, we suspect, is the *decision not to face the issue* . . . . If forced to choose, however, an organization is likely to dissolve—unless an innovation can be introduced" (Thompson and Tuden, 1959, p. 202; emphasis added).

A transformation in the way a problem is conceived may be a prerequisite for solving it.

In other words, if the political situation *requires* action, decision makers may reach a consensus about a mutually tolerable intervention but they are unlikely to "solve" the problem. Instead, the intervention will probably defer a solution or, at best, keep the problem from becoming intolerable. This phenomenon is known colloquially as "kicking the can down the road." Over the years, we have seen such outcomes for Social Security reform, immigration policy, resolving ethnic conflicts, and other complex issues.

Other scholars have argued that messy problems can be addressed using "heuristic decision making" (Gigerenzer and Gaissmaier, 2011) or creating an "organized anarchy," while adopting a "garbage-can" approach wherein solutions go looking for problems (Cohen et al., 1972).

As should be evident just from the terminology, these "strategies" are unlikely to offer policymakers much practical guidance, especially when dealing with large-scale messy problems. In our opinion, such strategies are poorly defined and difficult to implement, a weakness of more than academic interest. Our interest here is in describing a more practical and potentially formal way of approaching messy, complex problems.

Transformation as a Strategy

In many cases, and perhaps increasingly often, addressing messy problems cannot wait until divine guidance or political expediency saves the day. Nor can such problems be deferred indefinitely in the hope of fortuitously avoiding unacceptable consequences. Based on the cases we discuss below, problem solvers seem to have discovered, *at least implicitly*, approaches that offer some hope of success in tackling messy problems.

The essence of these approaches is the transformation of ill-structured challenges into well-structured ones. Such transformations, whether they are brought about by political or technical means, are always provisional and are generally contested, often vigorously, and whether a transformation can be made to endure remains an open question. Nevertheless, it seems that a durable transformation in the way a problem is conceived may be a prerequisite for solving it.

To illustrate this conclusion, we consider two archetypically messy problems, the management of high-activity radioactive waste and efforts to deal with global climate change.

Managing High-Activity Radioactive Waste

A strong consensus prevails in the international scientific community that the preferred method for ensuring the isolation and containment of high-activity radioactive waste is to dispose of it in a deep-mined geologic repository. Since the mid-1970s, more than a dozen countries have attempted (in some cases many times) to site such a facility, but only three of those efforts have culminated in the identification of a potentially suitable location and are still on track. The most important uncertainty related to siting is projecting repository behavior and performance for long periods of time, in some cases as long as a million years.

Depending on the nation, a variety of key values may be involved, such as how the development of a repository might affect the future production of nuclear-generated electricity, how the risk will be distributed between the host community and the rest of the country, and how questions associated with intergenerational equity will be answered.

We first examine how Sweden has addressed questions of uncertainty and value trade-offs. We then turn our attention to the experience in the United States.

Sweden

In the early 1970s, more than 50 percent of the energy used in Sweden was supplied by nuclear power. Thus, on a per capita basis, Sweden had made one of the largest commitments to nuclear power. By the mid-1970s, however, commercial nuclear power had emerged as a contentious political issue, with national parties staking out well-defined positions for and against.

The parliamentary election in 1976 brought into office a new coalition government that, at the beginning of the next year, passed the Nuclear Power Stipulation Act.[2] Among other things, the law mandated that, as a prerequisite for operations, the owners of power plants under construction *show how* and *where* the high-activity waste could be disposed of with *absolute safety* (see Sundqvist, 2002).[3]

Even after the passage of the Stipulation Act, however, the national debate over the future of commercial nuclear power continued unabated. In 1979, after the partial meltdown of the Three Mile Island reactor in the United States, all of Sweden's political parties endorsed an advisory referendum in which three policy options were put to the voters:

- The six reactors under construction or not yet operating would be allowed to start up, but nuclear power would be phased out "at a pace compatible with satisfying the need for electricity and maintaining employment and welfare" (Sundqvist, 2002, p. 94). No time limit was specified for the phaseout.
- Reactor start-ups would be permitted, but all reactors would have to be phased out within 25 years.
- The six reactors under construction or not yet operating would not be permitted to start up, and all operating reactors would have to be shut down within 10 years.

The first two options together received about 60 percent of the vote, the third slightly less than 40 percent. Interpreting the results of the referendum, Government decided that all plants could be started up but would have to be shut down by 2010. Notwithstanding the large minority that had supported an early shutdown of operating reactors and a moratorium on new ones, the referendum established a consensus on values that has persisted for more than three decades.[4]

The first test of the Stipulation Act was in December 1977, when an application was made to fuel the Ringhals 3 reactor located on Sweden's west coast. The Swedish Nuclear Fuel and Waste Management Company (SKB), which had been set up by reactor owners to develop a deep-mined geologic repository, engaged more than 450 scientists and engineers in a nine-month-long effort to demonstrate that its spent-fuel disposal concept would satisfy the requirements in the Stipulation Act.

A national referendum in Sweden established a consensus about nuclear reactors that has persisted for more than three decades.

This disposal concept, which was marginally modified over the next few years,[5] envisions the placement of high-activity waste in copper canisters. The canisters would be set in oversized boreholes drilled in the floor of the granite basement rocks that underlie most of Sweden. Bentonite clay would be used to fill the gaps between the canisters and the rock, and the repository itself would be sealed by backfilling the underground workings with bentonite.

Based on the laws of thermodynamics under the electrochemical conditions of the groundwater suffusing the

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[2] Of the coalition's three parties, only one, the Centre Party of the new prime minister, Thorbjörn Fälldin, was committed to shutting down operating reactors, halting construction on new reactors, and shelving plans for future reactors. The coalition fell apart in October 1978, primarily because of disagreements about nuclear energy policy.

[3] In 1984, the Nuclear Power Stipulation Act was replaced by the Nuclear Activities Act. Instead of "absolute safety," the new law provided for the establishment of dose constraints and risk targets to be met for as long as 10^6 years.

[4] Over that period, it became clear that there were few, if any, alternative sources for the production of baseload electricity. Two reactors, situated directly across the Öresund strait from Copenhagen, were shut down, but no action was taken with respect to the remaining ten plants. Then, recognizing that nuclear-generated electricity did not produce climate-changing gases, Parliament, by an overwhelming majority, lifted the ban on the construction of new nuclear reactors. After the vote, the leader of the Centre Party was quoted as saying, "I'm doing this for the sake of my children and grandchildren. I can live with the fact that nuclear power will be part of our electricity supply system in the foreseeable future" (*Guardian*, 2009).

[5] Among other things, the original concept anticipated the disposal of vitrified waste from the reprocessing of spent nuclear fuel. The concept finally adopted is based on the disposal of unprocessed spent nuclear fuel.

granite, the copper should not corrode. A natural analogue, elemental copper nodules in granitic formations that are tens of millions of years old, further increased confidence in the fundamental validity of the concept. And even if the containers did degrade, the bentonite clay would adsorb any radioisotopes that might migrate from them.

The Swedish waste management company established a long-term presence in the selected communities and formed bonds of trust.

In the late 1970s and again in 2000, this concept was rigorously peer-reviewed by both Swedish and international experts. Although questions have been raised recently about SKB's arguments with respect to copper corrosion, and other residual uncertainties persist, an international peer review just released by the Nuclear Energy Agency concluded that the concept was technically defensible (NEA, 2012).

In October 1978, the government coalition rejected the Ringhals 3 application under the Stipulation Act because SKB had failed to identify a *specific site* for the repository. However, the alliance left open the possibility that SKB could conduct supplemental geologic studies to demonstrate "that there exists a sufficiently large rock formation at the required depth and with qualities that the [SKB] safety analysis . . . gives as necessary prerequisites" (quoted in Sundqvist, 2002, p. 87). Any revised application would then be evaluated by the regulatory authority, then the Swedish Nuclear Power Inspectorate (SKI).

SKB immediately undertook additional investigations at two sites. Data from one of them, Sternö, on the southeast coast, were included in the amended application, which was submitted in February 1979. Notwithstanding a number of concerns raised by a technical advisory group empanelled by the regulators, the commissioners of SKI voted overwhelmingly a month later to approve SKB's request.

Although SKB had satisfied *in principle* the requirements of the Stipulation Act, thereby paving the way for the last six reactors to begin operation, selecting a suitable site *in practice* would take another 30 years. During that long process, the question of how to distribute risk between a host community and the rest of the nation—a key value trade-off—was gradually settled.

Shortly after the national referendum on nuclear power in 1980, a new nationwide search was initiated to find the best available geology for the final disposal of Sweden's nuclear waste. Test drillings conducted throughout the country, however, quickly gave rise to widespread local protests. By the end of the decade, SKB had reformulated its siting strategy, after recognizing that communities held a near-absolute veto over the development of a deep-mined geologic repository within their borders. In 1992, SKB sent a letter to all 286 Swedish municipalities, asking whether any of them would be interested in allowing "feasibility studies." The letter stressed that any expression of interest would be purely voluntary and could be withdrawn at any time. Although two municipalities in northern Sweden permitted studies to be conducted, both asked SKB to leave when local referenda revealed strong opposition by citizens.

SKB then turned its attention to municipalities located in or near four of the existing five nuclear communities and ultimately focused on two of them—Oskarshamn and Östhammar. The company established a long-term presence in both communities, interacting with residents in what appears to have been a sincere and respectful way and, by all indications, forming solid bonds of trust. In 2010, SKB formally chose Östhammar as the repository site largely on the basis of the soundness of the granite at that location. The overwhelming majority of the residents strongly support the development of the facility.

United States

In the United States, the 1982 Nuclear Waste Policy Act (NWPA) ratified four critical value trade-offs:

- Two repositories would be developed—one presumably in the west and one presumably in the east—to promote geographic equity.
- The site for a deep-mined geologic repository for high-activity radioactive waste would be chosen by comparing the *technical suitability* of at least three potential locations.
- In exchange for payment of a fee, nuclear utilities could enter into contracts that would require the

government to begin disposing of their high-activity waste by a date certain.

- State governments could veto the selection of a repository site, but the veto could be overridden by Congress.

Within four years, the trade-offs (i.e., bargains) had begun to fall apart. By 2010, the state of Nevada, whose veto of the selection of the Yucca Mountain site had been overridden by Congress eight years earlier, exercised its growing political influence to stop the waste management program in its tracks and force its fundamental reconsideration.

The NWPA required that the president submit a site recommendation for the first repository by March 31, 1987, and for the second repository three years later.[6] It further required that the Nuclear Regulatory Commission (NRC) prohibit the emplacement of more than 70,000 metric tons of heavy metal in the first repository until the second had begun operation.[7]

Notwithstanding the provisions of the law, the Reagan administration announced in May 1986 that the search for a site for the second repository would be suspended indefinitely because it would not be needed.[8] A bipartisan group of 13 key members of Congress warned the Secretary of Energy that this decision "could destroy the delicate balance and might ultimately lead to an erosion of the NWPA" (quoted in Colglazier and Langum, 1988, p. 333). How prescient that warning turned out to be!

The administration's decision to suspend the second repository program reflected growing and intense opposition, especially in the east, to the prospect of hosting a repository. In light of this political turbulence, coupled with projected increases in the cost of characterizing (investigating) sites, leaders in Congress were prompted to rethink another critical value trade-off—the technically based comparison of candidate locations. By then, the U.S. Department of Energy (DOE) had winnowed the number of potential sites from nine to five to three: a place in Deaf Smith County, Texas; the Hanford Site in Washington state; and Yucca Mountain near the Nevada Nuclear Test Site. Although DOE had ranked Yucca Mountain as technically suitable, it is clear that Nevada's (then) political weakness in Congress had been a significant contributing factor to the passage in 1987 of the Nuclear Waste Policy Amendments Act (NWPAA), which, among other things, limited site characterization to Yucca Mountain and officially terminated the second repository program.

Even though the number of sites to be evaluated had decreased dramatically, DOE routinely failed to meet the milestones in the NWPA and the agency's mission plans. By 1995, DOE acknowledged what had long been apparent: it would not be able to begin accepting waste from utilities by January 31, 1998, the deadline specified in the contract between the federal government and the nuclear utilities. In protracted litigation since then, the courts have uniformly ruled that the federal government is liable for damages incurred because of its failure to meet its contractual obligations. Although many of the nearly 80 claims filed have been settled, the federal government appears to be answerable for damages of more than $20 billion, assuming, improbably, that it begins accepting waste by 2020, and for approximately $500 million each year thereafter (BRC, 2012).

The steady erosion of critical value trade-offs helped destabilize the U.S. repository program.

One of the compelling technical reasons for limiting site characterization to Yucca Mountain was that the site was believed to be "dry." Water is the primary vehicle for transporting waste to the environment, and it was believed that the volcanic rocks in the Yucca Mountain site would reliably isolate and contain the deposited material for millennia. However, investigations of geologic formations often encounter surprises that force substantial adjustments in understanding. In the end, Yucca Mountain proved not to be a "dry" site, thus calling into question a central premise of the disposal concept (Metlay, 2000). In response, DOE transformed a "geologic" repository into a repository that relied heavily on engineered barriers, specifically waste packages fabricated from an esoteric corrosion-resistant alloy and drip shields fabricated from titanium, to satisfy the long-term performance requirements.

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[6] Section 114(a)(2)(A).

[7] Section 114(d).

[8] A year later, the Department of Energy determined that its suspension of the second repository program was illegal without action by Congress and prepared to restart the program. But by then it was too late as events had cascaded beyond control.

Once the original disposal concept had been destabilized by this new knowledge, other technical issues came to the fore. For example, how much water flows through the rock, and how fast does it flow? Might deliquescent salts corrode the waste packages through mechanisms that were not well understood (NWTRB, 2002, 2003)?

In 2008, convinced that these uncertainties had been resolved, DOE confidently submitted an application to the Nuclear Regulatory Commission for permission to construct the repository. In the course of the hearings that followed, the state of Nevada, which, as we will see below, had never faltered in its intense opposition to the repository, advanced nearly 300 technical and legal objections to the application. From the state's perspective, DOE's repository concept was not scientifically and technically defensible because significant uncertainties about the facility's long-term performance had not been adequately resolved.[9]

Key technical issues concern deep uncertainties about the costs and benefits of actions to reduce climate change or minimize its effects.

Nevada's opposition to the proposed Yucca Mountain repository is undoubtedly grounded in its view of the technical weaknesses in the disposal concept, but this view cannot be separated from the state's political opposition to the process that had led to the adoption of the NWPAA in the first place. (The law is referred to locally as the "screw Nevada" bill [e.g., Kishi, 2012].)

Politically weak in 1987, the state's political position in the Senate became stronger as Harry Reid rose in the Democratic leadership. In 2001, Reid came close to defeating the congressional override of the Nevada governor's veto of the selection of the Yucca Mountain site.

By 2006, Reid had become Senate majority leader and the most powerful political figure in Nevada. He leveraged his influence to come to an understanding with the three contenders in the Democratic Party's 2008 presidential primary that, if one of them were elected, he or she would terminate the Yucca Mountain project (Fialka, 2009). Not surprisingly, the Obama administration announced in January 2010 that it considered the project "unworkable" and that it would not support any additional appropriations for it. When DOE subsequently tried to withdraw its license application,[10] the last of the four bargains in the NWPA fell apart, despite the fact that the $13 billion spent on site characterization research had probably made Yucca Mountain the most carefully studied terrain on the planet.

Managing Climate Change

It is no secret that the world has not managed to develop a political approach to climate change, much less to the reduction of greenhouse gas emissions. Despite the enormous amount of scientific effort that has gone into characterizing the problem and the tremendous diplomatic and political capital expended to implement climate change policy at the international and national level, little progress has been made. Recent analyses of this failure have focused on the role of "merchants of doubt" in creating perceptions of uncertainty that have undermined political efforts (Oreskes and Conway, 2010). However, if we look at climate change as a messy problem, these analyses are incomplete and cannot point to a way forward.

The main technical counter-claim to opponents of action on climate change (which include some well-credentialed scientists) is that there exists a strong mainstream-scientific consensus about the reality and potential seriousness of anthropogenic climate change. We are inclined to agree that such a consensus exists, but it has little bearing on our argument.

The key technical issues that must be resolved are not about the existence of climate change per se, but about deep uncertainties related to the costs and beneficial impacts of actions to reduce climate change or minimize

[9] In 2011, a document was issued by the regulatory staff that did not include final conclusions about DOE's compliance with the environmental standards applicable to a deep-mined geologic repository. The document did, however, support virtually all of DOE's technical claims (NRC, 2011).

[10] In 2010, DOE established the Blue Ribbon Commission on America's Nuclear Future, charged with proposing a new path forward for developing a repository (BRC, 2012). In the meantime, the Nuclear Regulatory Commission's hearings were suspended without resolving the overwhelming majority of the technical objections raised by the state of Nevada. The D.C. Court of Appeals is now trying to sort out whether it should order that hearings be resumed, given the limited amount of appropriated funds available to conduct them. It is very unclear what the future holds for the waste management program in the United States.

its effects. In particular, the answers to questions about how to transform a global economy that depends on fossil fuels as its main source of energy into a non-fossil-fuel-based economy are irreducibly uncertain. Not only does the world have no experience managing complex socio-technical systems to control a single output variable (in this case, carbon emissions), but the interaction of scientific, technological, economic, and political variables is so complicated that it is unlikely a persuasive case can be made that clearly identifiable short-term costs (and their distribution) will be outweighed by uncertain future benefits.

In the following discussion, we highlight two apparently distinct aspects of this messiness. The first relates to using science to justify policy strategies. Climate change policies, like policies for nuclear waste disposal in the United States, were developed in a way that virtually guaranteed strong political opposition characterized by lack of trust in political and scientific claims about the selected policy solution—be it burying waste at Yucca Mountain or signing onto a United Nations agreement about climate change.

In the case of Yucca Mountain, scientists tried to prove that the site was safe to people living in a state in which most citizens, for various reasons, were irrevocably opposed to hosting the repository. In the case of climate change, scientists and policy advocates have tried to show that the reality of climate change demands a global policy agenda centered on top-down, United Nations–sponsored international agreements; targets and timetables for emissions reductions; and the creation of carbon markets. But in the United States, at least, significant segments of the population (especially political conservatives) typically distrust international governance regimes in general and the United Nations in particular; they strongly oppose government programs that require major transfers of wealth or overtly intervene in markets; and they are profoundly skeptical of government's ability to modify social behavior to achieve desired aims.[11]

In both cases examined here, opposition to the chosen policy regime has often been expressed in terms of uncertainty about the underlying science, which supposedly legitimates the policy regime. But behind the apparent skepticism about science is deeper political opposition.

A second aspect of the messiness of climate change seems, at least on its face, to be less about climate change politics per se than about the politics of steering technological change. To illustrate this point, one need only consider the increasingly intractable debates over the siting of solar power facilities in the United States; the apparently unexpected acceleration of fracking technologies that have radically increased recoverable U.S. natural gas reserves; and the renewal of controversies about nuclear power in the aftermath of the Fukushima disaster. In these instances we see, for example, disagreements among environmental advocates about the value implications of technical change—such as protecting undeveloped lands versus using those lands as sites for large solar farms that will generate clean energy.

Other disagreements focus on technical uncertainties about the future performance, cost, and environmental benefits of clean energy technologies. For example, the potential importance of increasing energy efficiency to reduce emissions is hotly contested. Private-sector competition for dominance over emerging markets is also involved, as those with business interests in competing technologies try to make the case for their particular sector. So politics are involved here, too, but not based on broad ideological commitments. Instead, the controversies are focused on intricate uncertainties and competing interests and values inherently involved in choices about technological pathways.

Taking seriously the political prerogatives of local municipalities can reinforce the credibility of scientific claims about safety and risk.

In the case of nuclear waste, Sweden has shown that taking the political prerogatives of local municipalities seriously can reinforce the credibility of scientific claims about site safety and risk. In the case of climate change, no widely accepted alternative to the broken global climate policy regime has yet emerged. Neverthe-

[11] For similar reasons, we anticipate that efforts to directly regulate carbon dioxide emissions in the United States through enforcement of the Clean Air Act will be unsuccessful. Any regulatory regime that could have a significant effect on emissions would also mobilize enormous, competing political and economic forces and, at the same time, trigger endless technical debates about efficacy, cost-benefit ratios, and so on.

less, the messy-problem perspective in general and the nuclear waste experience in particular suggest that policy approaches sensitive to particular political contexts and particular aspects of the larger climate problem will move things along much faster than increasing scientific research and development (R&D) on the causes and consequences of global climate change or offering apparently comprehensive solutions that promise to address the "whole" problem.

A pragmatic approach disaggregates climate change into less messy problems that are amenable to solutions that can attract a variety of constituencies.

One obvious opportunity to reduce the messiness of climate change policy is to reframe climate-energy policies to focus on both the economic and environmental opportunities of clean energy technology innovation. The creation of a new government organization for energy R&D, ARPA-E (Advanced Research Projects Agency–Energy), is one example of what appears to be a political success along these lines. Modeled after the politically popular Defense Advanced Research Projects Agency of the U.S. Department of Defense, ARPA-E is officially part of DOE but was conceived and promoted as a largely autonomous organization that would focus on high-risk, high-reward energy technology ventures, in collaboration with the private sector and universities (Bonvillian and Van Atta, 2012).

The case for the new agency was primarily based on arguments about the need to improve U.S. economic competitiveness and innovation in the energy domain. In fact, the legislation that created the organization was passed by a Republican-majority House of Representatives and signed into law by President George W. Bush. Although ARPA-E is neither justified by, nor administered with regard to, direct impacts on climate change, if it is successful in catalyzing energy technology innovation, it will undoubtedly help to open up new clean energy pathways.

Another potent avenue for eliminating some of the messiness of climate change is to develop policies that increase the capacity of societies to adapt to variations in climate regardless of what causes them. Policies might, for example, promote innovation in agriculture, water management, and the built environment.

Hurricane Katrina and the tsunami and earthquake that led to the devastation of the Fukushima nuclear power plant showed that the failure of engineered systems during extreme events can leave tens of thousands of people in jeopardy, even in the most affluent societies. But both events also showed that the strongest argument for better hazard mitigation rests on protecting society from *existing* exposure to a variety of types of familiar *known* hazards, thus side-stepping debates about the uncertain consequences of future climate change impacts. Mitigating hazards by promoting better land-use planning, stronger and better-enforced building codes, better-funded infrastructure maintenance programs, and relevant R&D not only makes political sense (independent of climate change), but also promises the sorts of concrete, near- to medium-term—and thus politically attractive—social returns on investment that climate change policies have been unable to offer (Sarewitz and Pielke, 2000, 2005).

The principles for a pragmatic, messy-problem approach to climate change were well developed more than a decade ago (see Rayner and Malone, 1999) and have more recently been articulated in the context of the clear breakdown of the United Nations process (e.g., Prins et al., 2010). A key attribute of such approaches is that they do not depend on reducing uncertainty about the long-term costs of climate change or the long-term benefits of action. Rather, they disaggregate climate change into multiple less messy problems that are amenable to solutions that can be advanced for a variety of purposes and thus can attract a variety of constituencies. Appropriate policies would provide shorter-term benefits independent of the long-term effects on reducing climate change, for example by increasing economic competitiveness and energy independence, reducing pollution and its public health effects, and improving the resilience of communities and nations to environmental stressors ranging from hurricanes to droughts to food shortages.

Unfortunately, because of the political stalemate in the United States today, and the climate debate in particular, even a pragmatic approach to problem transformation may now be greeted by climate skeptics as a

Trojan Horse that continues to advance the old climate policy agenda. However, we also note that these same kinds of pragmatic approaches to climate change have in the past been opposed by advocates of the old agenda as sops to those who really wished to do nothing at all. The point is that both sides of the debate have bought into a view of climate change that belies its fundamental and inescapable messiness.

Progress will depend on (1) agreement that climate change is, in fact, many problems (some of which are very familiar and uncontroversial), and (2) the pursuit of smaller-scale consensus on values and actions that promote focused scientific and engineering solutions to local, regional, and national problems.

Conclusion

In the mid-20th century a number of prominent social scientists recognized that conventional notions of scientific problem solving are of little help in understanding how societies and institutions cope with multifaceted problems that involve substantial uncertainties and contested values. Thompson and Tuden (1959) provided one formulation for thinking about the challenges of taking effective action in the face of such messiness. Other contributors to this tradition include Herbert Simon (1947), whose work focused on administrative behavior and bounded rationality; Charles Lindblom (1959), who realized that real-world problem solving is often best pursued by "muddling through"; and Harold Lasswell (1935), who developed the policy sciences for understanding complex, context-dependent policy problems.

We are particularly struck by the contrast between those works, which accept the messiness of many real-world problems, and the growing expectation in modern societies that natural science and engineering research will point the way toward solving them by reducing uncertainties about the future behavior of complex natural, social, and engineered systems.

We believe that this expectation will be continually confounded, and thus we have here sought to emphasize the importance of first transforming messy problems into well-structured problems by re-imagining the relationships between politics and science and technology. For example, the selection of the site for a nuclear waste repository in Sweden succeeded because it was based on the understanding that the political conditions that influenced the choice were as important as the scientific characterization of the site. Indeed, getting the politics right made it easier to get the science right. In the case of climate change, we have argued that the intractable uncertainties and disagreements that have undermined efforts to achieve a comprehensive policy can be evaded by disaggregating the messy climate problem into smaller, more familiar problems for which agreement on goals is possible.

Well-structured problems are stable because people can see—and potentially agree upon—near- or medium-term values to be pursued and can imagine capturing some of the benefits of pursuing them. However, stability cannot be reached for messy problems when (1) the problem itself, the possible routes to a solution, and the solutions themselves are subject to multiple, competing factual descriptions and value preferences, and (2) the uncertainties about the costs and consequences of actions remain high and highly contestable.

When problems are messy, scientific knowledge and technological options become unavoidably enmeshed in political disputes in ways that we have described (Metlay, 2000; Sarewitz, 2004). However, when problems are well structured and values are aligned with an understanding of what needs to be done, the role of science and engineering also comes into better focus. Knowledge and technology are no longer expected to resolve conflicting values and eliminate deep uncertainties, but are liberated to contribute directly to the pursuit of agreed-upon goals. Democratic politics and the scientific enterprise can both benefit from efforts to transform messy problems into well-structured ones.

References

Bonvillian, W., and R. Van Atta. 2012. The Energy Technology Challenge: Comparing the DARPA and ARPA-E Models. Pp. 46–56 in Energy Innovation at the Department of Defense: Assessing the Opportunities. Washington, D.C.: Consortium for Science, Policy and Outcomes and Clean Air Task Force. Available online at *www.cspo.org/projects/eisbu/reading.html*.

BRC (Blue Ribbon Commission on America's Nuclear Future). 2012. Report to the Secretary of Energy. Washington, D.C.: U.S. Department of Energy.

Cohen, M., J. March, and J. Olsen. 1972. A garbage can model of organizational choice. Administrative Science Quarterly 17:1–25.

Colglazier, W., and R. Langum. 1988. Policy conflicts in the process for siting nuclear waste repositories. Annual Review of Energy 13: 317–357.

Fialka, J. 2009. The "Screw Nevada Bill" and how it stymied

U.S. nuclear waste policy. *New York Times*, May 11, 2009.

Gigerenzer, G., and W. Gaissmaier. 2011. Heuristic Decision Making. Annual Review of Psychology 62: 451–482.

Guardian. 2009. Sweden lifts ban on nuclear power. February 5, 2009.

Kishi, S. 2012. Yucca Mountain. *Las Vegas Sun*, July 29, 2012.

Lasswell, H. 1935. Politics: Who Gets What, When, How. New York: McGraw Hill.

Lindblom, C. 1959. The Science of "Muddling Through." Public Administrative Review 19: 79–88.

Metlay, D. 2000. From Tin Roof to Torn Wet Blanket: Predicting and Observing Ground Water Movement at a Proposed Nuclear Waste Site. In Prediction: Science, Decision Making, and the Future of Nature, edited by D. Sarewitz, R. Pielke Jr., and R. Byerly Jr. Washington, D.C.: Island Press.

NEA (Nuclear Energy Agency). 2012. The Post-Closure Radiological Safety Case for a Spent Fuel Repository in Sweden. Paris: OECD/NEA.

NRC (Nuclear Regulatory Commission). 2011. Technical Evaluation Report on the Content of the U.S. Department of Energy's Yucca Mountain License Application. Washington, D.C.

NWTRB (Nuclear Waste Technical Review Board). 2002. Letter to Congress. January 24.

NWRTB. 2003. Board Technical Report on Localized Corrosion. November 25.

Oreskes, N., and E.M. Conway. 2010. Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. New York: Bloomsbury Press.

Prins, G., I. Galiana, C. Green, R. Grundmann, M. Hulme, A. Korhola, F. Laird, T. Nordhaus, R. Pielke Jr., S. Rayner, D. Sarewitz, M. Shellenberger, N. Stehr, and H. Tezuka. 2012. The Hartwell Paper: A New Direction for Climate Policy after the Crash of 2009. Available online at *www2.lse.ac.uk/researchAndExpertise/units/mackinder/theHartwellPaper/Home.aspxwww2.lse.ac.uk/researchAndExpertise/units/mackinder/theHartwellPaper/Home.aspx* (accessed June 21, 2012).

Rayner, S., and E. Malone. 1998. Ten Suggestions for Policymakers. Pp. 109–138 in Human Choice and Climate Change: What Have We Learned, Vol. 4. Edited by S. Rayner and E. Malone. Columbus, Ohio: Battelle Press.

Sarewitz, D. 2004. How science makes environmental controversies worse. Environmental Science and Policy 7: 385–403.

Sarewitz, D., and R.A. Pielke Jr. 2000. Breaking the global warming gridlock. The Atlantic Monthly (July): 54–64.

Sarewitz, D., and R. Pielke Jr. 2005. Rising tide: The tsunami's real cause. The New Republic January 17: 10–12.

Simon, H. 1947. Administrative Behavior: A Study of Decision-Making Processes in Administrative Organizations. New York: Free Press.

Steinbruner, J. 1974. The Cybernetic Theory of Decision: New Dimensions of Political Analysis. Princeton, N.J.: Princeton University Press.

Sundqvist, G. 2002. The Bedrock of Opinion: Science, Technology, and Society in the Siting of High-Level Nuclear Waste. Dordrecht, Netherlands: Kluwer Academic Publishers.

Thompson, J.D., and A. Tuden. 1959. Strategies, Structures, and Processes of Organizational Decision. Pp. 195–216 in Comparative Studies in Administration, edited by J.D. Thompson, P.B. Hammond, R.W. Hawkes, B.H. Junker, and A. Tuden. Pittsburgh, Pa.: University of Pittsburgh Press.

The principal causes of the Fukushima disaster were organizational culture and system complexity.

Complex Organizational Failures

Culture, High Reliability, and Lessons from Fukushima

Nick Pidgeon

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Most academics and practitioners in engineering quite rightly focus their attention on the science and performance of physical structures and systems, but delivering and operating engineered systems in an effective and safe manner has always depended on society and human beings. People, organizations, and ultimately their cultures are all involved in decisions about the design, building, and management of complex engineered systems. So, too, when things go badly wrong, people and their organizations are implicated in the events that led to the disaster. The recently published official Japanese inquiry into the Fukushima Daiichi nuclear accident acknowledges this with its description of the events as a "man-made disaster" (National Diet of Japan, 2012).

In addition to the human element, failures of complex engineered systems are rarely due to a single technical or environmental cause. Thus, although the Fukushima plants shut down as designed when the earthquake struck, the quake caused the loss of all off-site power to the complex. The subsequent tsunami then overwhelmed the flood defenses, destroying many of the remaining backup power and safety systems.

The inquiry report highlights other important contributory factors and concludes that this chain of events should have been foreseen and prevented. The site's vulnerability to loss of power in a major tsunami had been identified several years before the accident, but the report documents an insular and defensive attitude on the part of the plant's operator, Tokyo Electric Power Company (TEPCO), that, combined with a culture of deference and a cozy relationship with regulators, meant these and other safety warnings were not given sufficient priority. The result was a failure, over a number of years, to either properly examine the risks to the plant or improve safety measures.

This and other relatively recent examples of major system failure (e.g., the Deepwater Horizon oil spill in the Gulf of Mexico; Hopkins, 2012; Wassel, 2012, in this issue) are particularly disturbing because the underlying pathology of such situations has been well understood for more than 30 years. In this article I describe contributions of research in the social and engineering sciences to understanding of so-called socio-technical or man-made disasters.

The origins and causes of a major structural failure must be sought in the organizational and societal preconditions.

Man-Made Disasters and the "Climatology of Accidents"

Several seminal texts published within a decade of each other showed that major accidents do not simply happen on the day of the visible failure. They have a background, a social and cultural context, and a history. Taken together, the reports revealed that system complexity and an incomplete understanding of such complexity can defeat the best attempts at anticipating risks.

Writing in the *Proceedings of the First International Conference on Structural Safety and Reliability*, the structural engineer Sir Alfred Pugsley (1969) coined the phrase "engineering climatology of structural accidents." By this he meant the combination of political, financial, professional, and industrial pressures that may bear on a project to induce critical human errors or the oversight of critical safety issues that might lead to major structural failure. The final dramatic event might appear entirely technical in nature—a bridge or roof collapse, a major fire, a catastrophic aircraft fatigue failure—but the underlying origins and causes must be sought in the organizational and societal preconditions. The poorer the engineering climatology, the greater the likelihood of failure.

During the following decade detailed analytic work in engineering and the social sciences validated Pugsley's explanation. The British sociologist Barry Turner published his own account of major socio-technical system failures in his influential book *Man-Made Disasters* (1978). Based on careful analysis of common patterns underlying more than 80 accidents and disasters that occurred during a 10-year period in the United Kingdom (including major structural failures such as the collapse of the London Ronan Point apartment tower and the Aberfan mining debris disaster in South Wales), Turner found that all of them could be explained using theories of human and organizational behavior. He demonstrated that very few major accidents have a singular cause: it was far more typical to find that several precursor events had "incubated" to produce a situation he described as an "accident waiting to happen." In addition, surveying different domains, Turner showed that identical organizational and human causes recurred in seemingly disparate engineering sectors (e.g., structural, chemical, or electrical engineering), suggesting that engineers in different disciplines could learn vital lessons by talking to each other about failures.

Working independently of Turner, and drawing material from a range of prominent cases of civil engineering failures such as the collapses of the West Gate Bridge (Melbourne) and Tacoma (Wash.) Narrows Bridge, the structural engineer David Blockley (1980) arrived at similar conclusions in his book *The Nature of Structural Design and Safety*. According to Blockley, the practice and theory of engineering safety and reliability cannot progress without, first, greater attention to the organizational and political conditions that can induce human error and, second, the development of vulnerability metrics to measure such factors. Although these ideas are now widely accepted in engineering education, they were considered radical when first proposed.

System Complexity and "Normal Accidents": The Example of Three Mile Island

Theory and research on organizational accidents gained recognition outside the academic arena after the 1979 accident at the Three Mile Island (TMI) nuclear power plant in the United States and the subsequent publication of *Normal Accidents* by Charles Perrow (1984). Now one of America's foremost authorities on complex organizations, Perrow admitted that he came to the topic of risk and technology almost by accident (as it were), when he was invited by a former student to provide evidence to the President's Commission enquiring into the causes underlying the TMI nuclear accident. Perrow used a sociological approach to unravel the causes of the disaster, form his "normal accidents" thesis, and inform his book.

The TMI incident was the result of a series of minor failures: a seemingly inconsequential leak of water triggered a chain of events involving both technical component malfunctions and operator misunderstandings and errors. The collective outcome was a major loss of coolant, something that the recent tragic events in Japan once again demonstrate is still an Achilles' heel of the older generation of pressurized water reactors. No single contributory cause was sufficient to trigger the TMI meltdown (or indeed the Fukushima disaster), but taken together the events, not fully anticipated by the plant designers, conspired to defeat multiple safety systems designed to prevent loss of coolant.

Perrow concluded that the TMI accident was a direct consequence of the sheer complexity of the organizational and technical systems involved: some modern high-risk systems, such as nuclear power plants, are so complex as to be inevitably vulnerable to failure no matter how well managed. As Perrow put it, they eventually suffer a "normal accident." However, inasmuch as background preconditions likely incubate over relatively long periods of time, there is at least some possibility of detection and prevention, even for highly complex systems.

For his analysis of system complexity, Perrow developed the concepts of "interactive complexity," meaning the number and degree of system interrelationships, and "tight coupling," or the degree to which initial failures can rapidly concatenate to affect the functioning of other parts of the system. Universities, for example, are interactively complex but only loosely coupled, whereas modern production lines often have tight coupling but typically rely on simple linear interactions. Neither tends to suffer systemic accidents. But a high-risk system with both high complexity and tight coupling, as at TMI, may require radical redesign or even abandonment of the technology entirely.[1]

[1] Perrow's account implies that simply adding more safety devices—the standard response to the previous unanticipated failure—might paradoxically *reduce* margins of safety if they add to the opaqueness and complexity of the system.

Perrow's analysis of the TMI incident can be supplemented by insights from man-made disaster theory, which describes the background organizational, management, and communication failings that occur in the days, months, and years before an accident. The precise events at TMI, as is now known, had been foreshadowed by similar near-miss events in other U.S. pressurized water nuclear plants, raising the question of why safety information and learning were not shared among the various organizations involved (Hopkins, 2001).

Complex high-risk systems may be vulnerable to failure no matter how well managed, and eventually suffer a "normal accident."

These insightful analyses of major accidents were unfortunately followed in very short order by a string of major technological disasters around the globe during the 1980s (e.g., the *Challenger* explosion, the Chernobyl nuclear disaster, and the gas leak in Bhopal), all of which called for sophisticated analysis. In light of the arguments for examining technological failures as the product of complex interacting systems, and the identification of the critical roles of organizational and management factors as primary causes of failures, such "technological" disasters could no longer be ascribed, as previously, to isolated malfunctions, operator error, or "random acts of God."

High-Reliability Organizations and Safety Cultures

The 1980s not only were important for crystallizing and disseminating new theories of organizational accidents but also served as an intellectual turning point. By the 1990s it was clear that, while there was a need for analysis of the causes of past accidents, analysts also had to consider ways to improve safety management in complex engineered systems. How might engineers and risk managers encourage organizational safety? Could it be designed?

Of course, in a straightforward sense, risk and safety must always be considered together, and the goal of related research is to help improve safety and resilience. However, understanding how vulnerability to failures and accidents arises does not automatically confer predictive knowledge to prevent future catastrophes. The question then becomes, can a theory of vulnerability to error and failure be used to build a theory of resilience and safety (e.g., Blockley, 1992)?

Perrow's approach embodied a tension between foresight and fatalism. Studies over the past two decades have explored this tension through analysis of high-reliability organizations and safety culture.

An organization is defined as much by what its members attend to as by what they choose to ignore.

High-Reliability Organizations

Researchers who examined high reliability worked from very detailed empirical case studies (e.g., concerning flight operations aboard aircraft carriers) in which the conditions for normal accidents existed but the systems operated safely and reliably on a day-to-day basis (Roberts, 1993). The results of their examination indicated that research on the conditions leading to failures should be supplemented by studies of successful risk management.

Analysts identified the following organizational and cultural factors as key reasons for the safe management of the otherwise toxic combination of high system complexity and high risk (see, e.g., Weick and Sutcliffe, 2001).

- Collective "mindfulness" is the idea that a design or operations teams can, by collaborating, develop a more comprehensive picture than that of any one individual alone.
- Group norms stressing open communication and deference to expertise (wherever it resides in the organization) can promote identification and response to signs of rapidly escalating failure conditions before the onset of a full-scale disaster.
- High-reliability organizations place a heavy premium on maximizing long-term learning opportunities, both within the organization and from other related industrial organizations and sectors, to identify and address underlying systemic faults before they combine with other events.

Discussions of high-reliability organizations eventually played out with no satisfactory resolution of the fundamental question at hand: Were normal accidents inevitable, as authors such as Sagan (1993) argued, or could complex systems indeed be safely managed as the high reliability researchers claimed? Part of the problem lay in the inherent difficulty of identifying a truly normal accident (which, by definition, is very rare) and part in the impossibility of definitively proving that a system was reliably safe (beyond the absence of any history of accidents).

Both the normal accident and high-reliability approaches are now viewed less as traditional theories, which would yield propositions falsifiable through clear empirical tests, and more as "sensitizing concepts" that enable a more effective approach to thinking about how high-risk systems both work and fail (Rijpma, 1997).

Safety Culture

Accident prevention research focused on the somewhat different concept of safety culture. In a development now likely to be replayed in light of the conclusions of the Fukushima inquiry report, intense academic and regulatory interest in safety culture followed the accident at Chernobyl in 1986. The errors and violations of operating procedures that contributed to the disaster were described as evidence of a poor safety culture both at the plant and in the former Soviet nuclear industry more generally (OECD Nuclear Agency, 1987).

Implicit in the man-made disasters model was a view of culture in terms of the symbols and systems through which a given group or profession understands the world. A safety culture is built on assumptions and associated practices that inform beliefs about danger and safety. Such a culture is repeatedly created and recreated as members behave and communicate in ways that seem to them natural, obvious, and unquestionable and as such contribute to a particular version of risk, danger, and safety.

To maximize the chances that an organization can recognize and respond appropriately to signs of potential emerging hazards, a good safety culture should reflect at least four facets (Pidgeon and O'Leary, 2000):

- senior management commitment to safety,
- shared care and concern about hazards and their impacts on people,
- realistic and flexible norms and rules about dealing with risks, and
- continual reflection on and improvement of practice through monitoring, analysis, and feedback systems (organizational learning).

In exploring safety cultures as a route to resilient technical systems it is thus necessary to go beyond individual attitudes about safety to the level of shared thinking and the administrative structures and resources that support, rather than constrict, the development of organizational understandings of risk and danger.

The Importance of Organizational Learning

It is clear that organizational learning is a key component of both good safety cultures and high-reliability organizations (Pidgeon, 1997). But learning can be thwarted by well-known difficulties in handling information—too much information, inappropriate communication channels, incomplete or inappropriate information sources, or failure to connect available data—and these difficulties can pose acute challenges for safety. For example, an incomplete or inaccurate problem representation might develop at the level of the organization as a whole and thus influence the interpretations and decisions of the organization's individual members. Such a representation may arise through organizational rigidity of beliefs about what is and is not to be considered a "hazard."

The Fukushima disaster is an instructive example of such organizational thinking. The plant owners developed a group mindset about the risks of tsunami, minimizing the significance of the knowledge that flooding across the site could lead to a total loss of power (and hence the cooling function). They also failed to take account of the risk of a tsunami larger than the projections made by the Japanese Society of Civil Engineers, even though it was clear that such an event could disable the plant and seriously damage the reactors, with catastrophic consequences.

The lack of adequate preparation at Fukushima illustrates the point that an organization is defined as much by what its members attend to as by what they choose to ignore. As Dianne Vaughan succinctly put it in her detailed analysis of the *Challenger* Space Shuttle disaster, a deficient safety culture at NASA "provided a way of seeing that was simultaneously a way of not seeing" (Vaughan, 1996, p. 392).

Avoiding disaster therefore involves an element of thinking both within defined frames of reference to deal with well-defined hazards that fall within an organization's existing worldview, and outside those frames to at least consider the possibility of emergent or ill-defined hazards that have not been identified or that perhaps fall outside an individual's or organization's strict professional or legal remit. In effect, engineers should cultivate the art of scanning for the unintended consequences of their decisions—they should embrace the use of what I call "safety imagination"—as a routine part of their professional practice.

BOX 1
Guidelines for Fostering "Safety Imagination"

- Attempt to envision the worst
- Use good meeting management techniques to elicit varied viewpoints
- Play the "what if" game with potential hazards
- Actively elicit and consider all worst-case situations
- Suspend assumptions about how the safety task was completed in the past
- Recognize that a tolerance of ambiguity will be required, as newly emerging safety issues will never be clear
- Visualize "near miss" situations developing into accidents

Source: Adapted from Thomas, 1994.

Box 1 provides one of the best checklists for safety imagination I have yet to come across, although it was not created as such. The list is adapted from teaching materials developed for training firefighters in the U.S. Forest Service (Thomas, 1994). Most fire service training revolves around a military style of command and control, emphasizing hierarchical organizational structure and response, since many of the hazards involved in firefighting are well known and relevant precautions or procedures can accordingly be specified and trained for in advance. Some hazards, however, are far less well understood by firefighters on the ground. For such circumstances, and for any professional facing a potentially ill-structured and changing risk system, the points in Box 1 outline a useful approach.

The intention of the guidance presented in Box 1 is to counter well-known information difficulties and organizational rigidities of thinking by

- extending the scope of potential scenarios relevant to the risk issue at hand (e.g., by eliciting varied viewpoints, playing the "what if" game, visualizing near misses becoming accidents),
- countering complacency and the view that "it won't happen here" (i.e., always fear the worst, thoroughly consider worst-case scenarios),
- forcing the recognition that during an incubation period the most dangerous ill-structured hazards are by definition surrounded in ambiguity and uncertainty (i.e., tolerate ambiguity), and, perhaps most critically,
- attempting to step temporarily beyond, or even suspend, institutionally defined assumptions about what the likely hazard and its consequences will comprise (i.e., suspend assumptions about how the safety task was completed in the past).

Concluding Comments

In light of recent serious challenges, it is clear that the lessons to be gained from analyses of past organizational accidents and disasters may need to be learned all over again by a new generation of engineers, risk regulators, and industry managers. The inquiries following Fukushima highlight the fact that the importance of cultural and organizational factors should never be underestimated (and it would be a further mistake to attribute these events to the unique culture and society of Japan).

For engineers interested in seeking to understand and manage complex risks, theories of high-reliability organizations, safety culture, and organizational accidents should be required reading. Failure to anticipate hazards in complex engineered systems is an affliction that can strike anybody, any time, and anywhere!

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References

Blockley, D.I. 1980. The Nature of Structural Design and Safety. Chichester, U.K.: Ellis Horwood.

Blockley, D.I. 1992. Engineering Safety. London: McGraw Hill.

Hopkins, A. 2001. Was Three Mile Island a "Normal Accident"? Journal of Contingencies and Crisis Management 9(2): 65–72.

Hopkins, A. 2012. Disastrous Decisions: The Human and Organisational Causes of the Gulf of Mexico Blowout. Sydney: CCH Australia.

National Diet of Japan. 2012. Fukushima Nuclear Accident Independent Commission (NAIIC) Final Report, edited by K. Kurokawa et al. Tokyo.

OECD Nuclear Agency. 1987. Chernobyl and the Safety of Nuclear Reactors in OECD Countries. Paris: Organization for Economic Cooperation and Development.

Perrow, C. 1984. Normal Accidents: Living with High Risk Technologies. New York: Basic Books.

Pidgeon, N.F. 1997. The limits to safety? Culture, politics, learning and man-made disasters. Journal of Contingencies and Crisis Management 5(1): 1–14.

Pidgeon, N.F., and M. O'Leary. 2000. Man-made disasters: Why technology and organizations (sometimes) fail. Safety Science 34: 15–30.

Pugsley, A.G. 1969. The engineering climatology of structural accidents. Pp. 335–340 in Proceedings of the First International Conference on Structural Safety and Reliability (ICOSSAR I). Washington.

Rijpma, J. 1997. Complexity, tight coupling and reliability: Connecting normal accidents with high reliability theory. Journal of Contingencies and Crisis Management 5(1): 15–23.

Roberts, K.H. 1993. New Challenges to Understanding Organizations. New York: MacMillan.

Sagan, S.D. 1993. The Limits of Safety: Organizations, Accidents, and Nuclear Weapons. Princeton, N.J.: Princeton University Press.

Thomas, D. 1994. Prescribed fire safety: Preventing accidents and disasters, Part II. Unit 2-G in course Prescribed Fire Behavior Analyst. Marana, Ariz.: National Advanced Resource Technology Center.

Turner, B.A. 1978. Man-made Disasters. London: Wykeham Science Press.

Vaughan, D. 1996. The *Challenger* Launch Decision: Risky Technology, Culture, and Deviance at NASA. Chicago, Ill.: Chicago University Press.

Wassel, R. 2012. Safer offshore drilling: Lessons from the Macondo well blowout in the Gulf of Mexico. The Bridge 42(3): 46–53.

Weick, K.E., and K.M. Sutcliffe. 2001. Managing the Unexpected: Assuring High Performance in an Age of Complexity. San Francisco, Calif.: Jossey-Bass.

Risk perception and communication are important factors in decisions about managing risk events and their impacts.

A Perspective on the Social Amplification of Risk

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One of the most perplexing problems in risk analysis is why some relatively minor risks or risk events (as assessed by technical experts) elicit strong public concerns and result in substantial impacts on society and the economy. Such concerns and impacts are typically the result of "social amplification"—changes in risk perception and response based on psychological, social, institutional, and cultural processes. Social amplification is most likely to flourish when the risks are serious and the situation is fraught with uncertainties.

In this article I describe a tool, the social amplification of risk framework, for understanding and accounting for public attitudes toward risk. The framework links the technical assessment of risk with psychological, sociological, and cultural perspectives of risk and risk-related behavior (Kasperson et al., 1988; Pidgeon et al., 2003). The main thesis of the framework is that hazards interact with these perspectives in ways that may amplify or attenuate public responses. In this article I focus on amplification.

Risk amplification typically occurs at two stages in a risk scenario: in the transfer of information about risk and in social response mechanisms. Signals about risk are both transmitted and processed by individuals and social entities, called "amplification stations." The individual might be a scientist, for example, who communicates the risk assessment; a social entity might be the news media, a cultural group, or an interpersonal network. The perceived amplified risk leads to behavioral responses that result in secondary impacts or "ripples."

Social amplification may qualitatively and quantitatively increase not only the perception of risk but also the risk itself and its consequences. For this reason, social amplification of risk must be included in analyses of public and regulatory reactions to risk events.

The key amplification stages are listed below:

- filtering signals (only a fraction of all incoming information is actually processed)
- decoding and reframing signals
- processing risk information (e.g., drawing inferences)
- attaching social values to information as a basis for drawing implications for management and policy
- interacting with cultural and peer groups to interpret and assess the validity of signals
- formulating behavioral intentions about whether to tolerate a risk or take action against the risk or risk manager[1]
- engaging in group or individual actions to accept, ignore, tolerate, or change the risk

The Framework: Terms and Definitions

The starting point in the social amplification framework is a risk event, which might be an actual or hypothesized incident (or even a new report about a known risk) and which may be minimal, largely irrelevant, or localized in its impact, unless it is observed and communicated to others and thus amplified. The characteristics of the risk are then portrayed through communication signals that interact with psychological, social, institutional, and/or cultural processes in ways that intensify perceptions of the risk and its manageability.

Individuals perceive risks through the lens of organizational values and cultural biases.

The experience of risk thus involves not only concern about potential physical harm but also interpretation of risk by groups and individuals. The social amplification of risk framework enables effective assessment of this multidimensional risk experience, secondary and tertiary consequences, and the actions of risk managers, stakeholders, and the public.

The term "amplification" (which comes from classical communication theory) refers to the process of various social agents generating, receiving, interpreting, and passing along risk signals, which are always changed in the process.[2] In fact, risk signals are subject to predictable "transformations" as they filter through social and individual amplification stations. The social amplification stations generate and transmit information via communication channels such as mass media, social media, letters, telephones, and face-to-face conversations; Figure 1 illustrates the many sources, channels, and filters of information that combine to transform risk perception. The transformations may increase or decrease the volume of information about an event, heighten the salience of certain aspects of a message, or reinterpret and elaborate available symbols and images, leading to particular interpretations and responses by those who next receive the information.

Individual amplification stations are affected by "risk heuristics" (i.e., qualitative aspects of the risk and context such as attitudes, blame, or trust). Individuals are also members of cultural groups and other social units (social stations of amplification) that codetermine their risk perception (Dietz and Stern, 2008). Individuals in groups and institutions do not simply pursue their personal values and social interpretations; they perceive risks, those who manage them, and the risk problem through the lens of values of the organization or group and, perhaps, its cultural biases (Dietz and Stern, 1996).

Social amplification also accounts for the secondary and tertiary consequences, or ripples (illustrated on the right side of Figure 1), of some events. Like ripples in a pond, they may spread far beyond the initial point of impact and may even affect previously unrelated groups or institutions.

Ripple Effects

Imagining ripples in a pond is a good way to think about how impacts associated with the social amplification of risk spread outward (Figure 1), from those

[1] "Risk manager" refers here to a public- or private-sector agency rather than an individual.

[2] In this context, *amplification* does not explicitly or exclusively mean *intensification* or *elaboration*. It also means the *modification* of information as it is transmitted from one source to another and received through the filters of personal, social, cultural, and other biases.

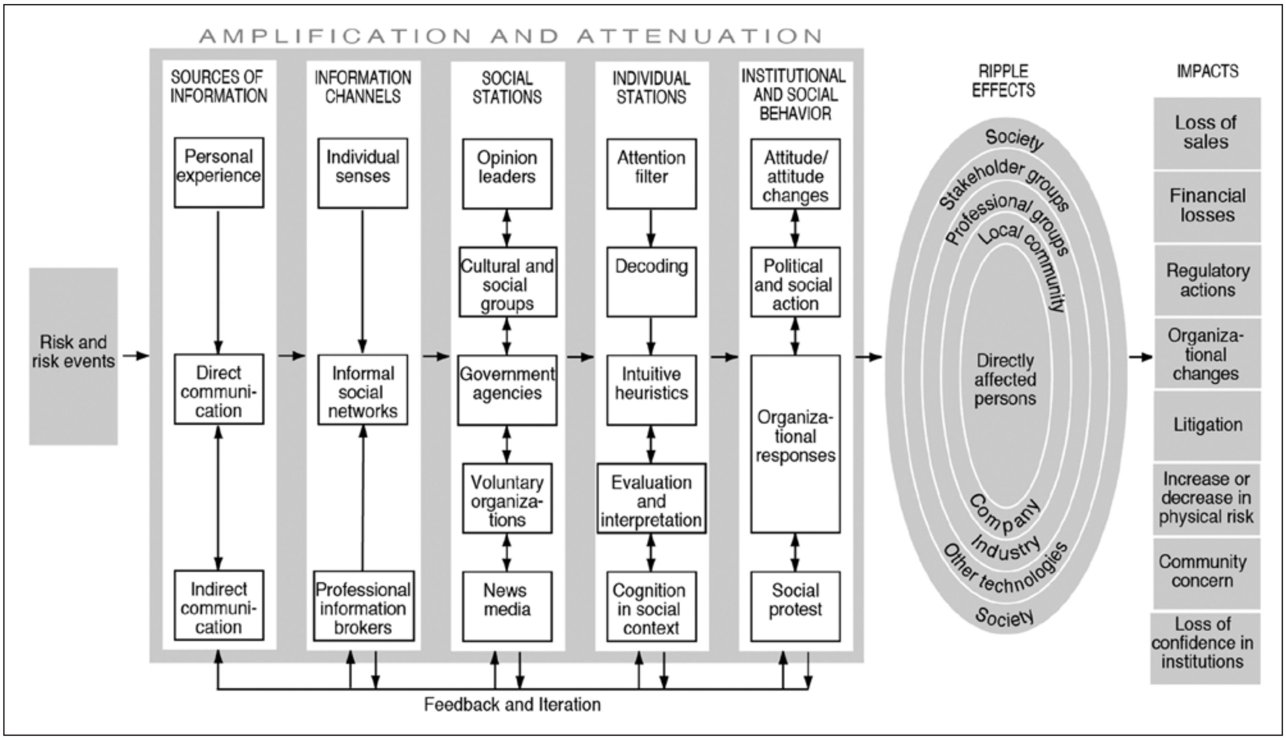

FIGURE 1 Social amplification of risk framework.

directly affected (or first notified) to the next, institutional level (a company or an agency), and, in some cases, to other parts of an industry. For example, in the wake of the Deepwater Horizon explosion in April 2010, the effects spread from the drilling rig to the rest of the Gulf of Mexico, including the wetlands and beaches in all of the adjacent states, and then to politicians and petroleum industry representatives who were compelled to reconsider their plans to expand offshore drilling.

The concept of rippling impacts suggests processes that can extend (in risk amplification) or constrain (in risk attenuation) temporal, sectoral, and geographical impacts. It also illustrates that each order of impact, or ripple, may not only have social and political effects but also trigger (in risk amplification) or hinder (in risk attenuation) managerial interventions to reduce risk.

Secondary effects include market impacts (e.g., consumer avoidance of a product or related products), demands for regulatory constraints, litigation, community opposition, loss of credibility and trust, stigmatization of a facility or community, and investor flight. They may also include some or all of the following effects:

- enduring changes in perceptions, images, and attitudes (e.g., antitechnology attitudes, alienation from the physical environment, social apathy, stigmatization of an environment or risk manager)
- losses in local business sales, lower residential property values, and lower levels of economic activity
- political and social pressure (e.g., political demands, changes in the political climate and culture)
- changes in the nature of the risk (e.g., feedback mechanisms that heighten or lower the risk)
- changes in training, education, or required qualifications for operations and emergency response personnel
- social disorder (e.g., protests, riots, sabotage, terrorism)
- changes in risk monitoring and regulation
- higher liability and insurance costs
- repercussions on other technologies (e.g., lower levels of public acceptance) and on social institutions (e.g., erosion of public trust), as when the 1989 explosion at the chemical plant in Bhopal, India, raised concerns about the possible failure of “fail-safe” systems at nuclear power plants.

Once secondary impacts are perceived by social groups and individuals, they may lead to another stage of amplification and tertiary effects that may affect other parties, more distant locations, or future generations.

Each order of impact may also trigger (in risk amplification) or hinder (in risk attenuation) positive changes for risk reduction. Examples of positive changes were apparent in the wake of the Fukushima nuclear accident in Japan when Germany restructured its energy system and the United States (among other countries) launched a major review of its nuclear plants.

Uncertainty Analysis

Uncertainty is inescapable, even in familiar situations—such as crossing a street or driving a car—but such quotidian uncertainty usually remains within reasonable bounds. People rely on existing knowledge and experience to guide future expectations.

But contexts change, and new elements affecting risk unexpectedly appear. For highly complex systems with extensive connectivity and interactions, or novel problems or technology for which experience provides little guidance, decisions must often be made quickly and under conditions of high uncertainty, greatly complicating the assessment of risk.

Uncertainty may arise from gaps in data, insufficient models, or incomplete scientific understanding of a risk. Depending on the type and source of uncertainty, new information and more data may not reduce it. As was noted in *Thinking Strategically*, a 2005 National Research Council report, scientific progress may not only reduce some uncertainties but also uncover new ones (NRC, 2005).

It is not surprising that—in a world of complex systems involving rapid technological change, highly coupled human and natural systems, and a kaleidoscope of social, economic, and political institutions—high levels of uncertainty challenge existing assessment methods as well as public consideration and communication of risk decision and management procedures. In *Science and Decisions: Advancing Risk Assessment* (NRC, 2009), a committee of experts identified six core principles for addressing uncertainty and vulnerability (Box 1).

BOX 1
Recommended Principles for Uncertainty and Variability Analysis

1. Risk assessments should provide a quantitative, or at least qualitative, description of uncertainty and variability consistent with available data. The information required to conduct detailed uncertainty analyses may not be available in many situations.
2. In addition to characterizing the full population at risk, attention should be directed to vulnerable individuals and subpopulations that may be particularly susceptible or more highly exposed.
3. The depth, extent, and detail of the uncertainty and variability analyses should be commensurate with the importance and nature of the decision to be informed by the risk assessment and with what is valued in a decision. This may best be achieved by early engagement of assessors, managers, and stakeholders in the nature and objectives of the risk assessment and terms of reference (which must be clearly defined).
4. The risk assessment should compile or otherwise characterize the types, sources, extent, and magnitude of variability and substantial uncertainties associated with the assessment. To the extent feasible, there should be homologous treatment of uncertainties among the different components of a risk assessment and among different policy options being compared.
5. To maximize public understanding of and participation in risk-related decision-making, a risk assessment should explain the basis and results of the uncertainty analysis with sufficient clarity to be understood by the public and decision-makers. The uncertainty assessment should not be a significant source of delay in the release of an assessment.
6. Uncertainty and variability should be kept conceptually separate in the risk characterization.

Source: NRC, 2009, p. 120.

Management Strategies

Management strategies have evolved for determining the interrelationships between types of uncertainty and decision patterns (Funtowicz and Ravetz, 1990). For situations in which uncertainties and decision stakes are low, standard routines and procedures usually suffice for making decisions. As stakes and uncertainties increase, professional consultants and other experts may be called upon. Finally, risks characterized by high-stakes decisions and significant uncertainty require the involvement of "post-normal science," which applies when "facts are uncertain, values in dispute, stakes high, and decisions urgent" (Funtowicz and Ravetz, 1991). Social amplification is especially likely to be a compounding factor in such cases, for both assessment and decision making.

While there is little question about the challenges of risk uncertainty and social amplification for the scientific community, they are not issues for the scientists alone. They greatly affect people and environments far beyond science. Uncertainty and amplification reflect differences in patterns of vulnerability, in the natural environment, in social and cultural communities, and in ambiguities surrounding the choice of management approaches and interventions.

Risk assessment is based on an assumption that sufficient knowledge and quantification can be achieved to enable command-and-control strategies and regulation. But much depends on the extent of both residual uncertainties and amplification, whether they can be reduced significantly, and how they affect the acceptability of the risk.

Large uncertainties and social amplification may necessitate alternative management approaches. Adaptive management strategies (e.g., "going with the flow" and making midcourse corrections) are based on the presence of substantial uncertainty and the understanding that knowledge is coevolving with the risk. The effectiveness of such approaches depends on the risk and the extent to which midcourse corrections can be made in technology, siting, and project design and how extensively amplification affects decision options.

Conclusion

A particular policy strength of the social amplification of risk framework is its capacity to mesh emerging findings from different venues of risk and impact research, to bring various insights and analytic leverage into conjunction, and (particularly) to analyze connections and interactions in specific social and cultural contexts. Because of its broad applicability and inclusion of a wide variety of factors and linkages, this framework is useful for teasing out patterns and broader interpretations that may yield new insights and hypotheses.

Yet, even with 15 years of experience since this framework was set forth, a full-fledged theory that explains why some risks and risk events undergo more or less amplification or attenuation has yet to emerge. There is more to study and learn in this evolving field of research.

References

Dietz, T., and P. Stern, eds. 1996. Understanding Risk. Washington, D.C.: National Academy Press.

Dietz, T., and P. Stern, eds. 2008. Public Participation in Environmental Assessment and Decision Making. Washington, D.C.: National Academies Press.

Funtowicz, S.O., and J. Ravetz. 1990. Global Environmental Issues and the Emergence of Second Order Science. London, U.K.: Council for Science and Society.

Funtowicz, S.O., and J.R. Ravetz. 1991. A new scientific methodology for global environmental issues. Pp. 137–152 in Ecological Economics: The Science and Management of Sustainability, edited by R. Costanza. New York: Columbia University Press.

Kasperson, R.E., O. Renn, P. Slovic, H.S. Brown, J. Emel, R. Goble, J.X. Kasperson, and S.J. Ratick. 1988. The social amplification of risk: A conceptual framework. Risk Analysis 8(2): 177–187.

NRC (National Research Council). 2005. Thinking Strategically. Washington, D.C.: National Academies Press.

NRC. 2009. Science and Decisions: Advancing Risk Assessment. Washington, D.C.: National Academies Press.

Pidgeon, N., R.E. Kasperson, and P. Slovic, eds. 2003. The Social Amplification of Risk. Cambridge, U.K.: Cambridge University Press.

Public responses to the recommendations of the Blue Ribbon Commission on America's Nuclear Future are generally positive.

Designing a Process for Consent-Based Siting of Used Nuclear Fuel Facilities—Analysis of Public Support

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U.S. policies for long-term management of used nuclear fuel (UNF[1]) have been placed on hold in the wake of the Obama administration's decision to withdraw the license application for the proposed Yucca Mountain repository. After President Obama declared that the Nevada repository specified in the 1987 Amendments to the Nuclear Waste Policy Act was "unworkable," he directed Secretary of Energy Steven Chu to charter the Blue Ribbon

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[1] The terms "used" and "spent" nuclear fuel refer to the same materials, but they imply important differences in whether the materials are considered resources or wastes. In this article, we use the term "used nuclear fuel" (UNF) because we do not wish to suggest that the materials have no possible future utility.

Commission on America's Nuclear Future (BRC) to formulate recommendations for a new approach to the management of UNF.[2] One of the major conclusions of the BRC was that prior policy efforts have not garnered sufficient trust and confidence from the public or the prospective host state. To address these concerns, the BRC's recommendations, delivered in January 2012, included the following key elements (BRC, 2012)[3]:

- The United States should undertake prompt efforts to develop one or more geologic disposal facilities and one or more consolidated (interim) storage facilities.
- A new consent-based approach should be developed and implemented for siting UNF storage and disposal facilities, but the design of the consent process should not be specified and the definition of "consent" should be part of the negotiation of the process.
- The responsibility for the siting and operation of UNF interim and permanent repositories should be shifted from the U.S. Department of Energy (DOE) to a federally chartered corporation.

Given the importance of public trust and confidence to a sustainable and successful UNF management process, the focus of this article is on likely public perceptions and response to the BRC's core recommendations. Our findings are based on data collected by the National Security and Nuclear Policies (NSNP)[4] project, which has measured public perceptions and beliefs about nuclear energy and the management of UNF annually since 2006. In a previous article in this journal (Jenkins-Smith et al., 2012) we addressed how policy and facility design considerations for UNF management relate to public acceptance.

In this follow-up article, we present findings from the June 2012 NSNP survey related to public understanding of current UNF management practices and investigate potential public reactions to the principles of consent-based siting recommended by the BRC. We measure (1) levels of public support for permanent and interim storage concepts, (2) credibility and perceptions of bias in institutional risk assessments, and (3) what constitutes "consent" for siting UNF facilities and how and when it may be granted and withdrawn. Our goal is to assess how readily the BRC's proposals might garner broad public support during the initial stages of policy development.

Public Preferences for Storage Practices for Used Nuclear Fuel

Unless UNF management practices are implicated by large-scale adverse nuclear events (such as the earthquakes and subsequent tsunami that struck Japan on March 11, 2011),[5] the level of public attention paid to UNF management policies is typically lower than it is for many other policy issues, such as the state of the economy and access to health care.

In fact, most members of the public do not seek out information about current UNF policies. Only 4 in 10 respondents in 2012 knew that UNF is being temporarily stored in cooling pools and specialized concrete casks at or near U.S. nuclear power plants at more than 100 sites in 39 states.[6] Only 14 percent knew whether UNF was being stored in their state of residence. In short, even in the aftermath of the well-publicized Fukushima nuclear event, details associated with UNF are not generally well known to the American public.

Most Americans are not well informed about used nuclear fuel storage practices or locations.

When measuring public assessments of complex policy issues about which knowledge and information levels vary widely, a phased approach in which basic factual information is provided in stages can ensure that respondents are at least minimally informed before they are asked for their opinions and policy preferences. After advising participants of current UNF temporary

[2] See the charter for the BRC at *www.brc.gov/index.php?q=page/charter*.

[3] The BRC's final report (BRC, 2012) can be found here: *www.brc.gov*.

[4] The NSNP project's annual surveys are sponsored by Sandia National Laboratories and the University of Oklahoma. For an overview, see Herron, Jenkins-Smith, and Silva (2012). Past reports are available at *http://crcm.ou.edu/projects/nuclear/*.

[5] NSNP measurements in 2011 and 2012 indicate that public support for U.S. nuclear energy production was only slightly adversely affected by the Japanese experience (a mean decline in support of –1.46 on a scale of –10 [strongly decreased support] to +10 [strongly increased support]).

[6] As noted in Jenkins-Smith et al. (2012), NSNP measurements over time indicate slowly growing public awareness of current UNF management practices from 1 in 5 respondents in 2006 to 4 in 10 respondents in 2011 and 2012.

TABLE 1 Public Preferences for Alternative UNF Storage Concepts (2012)

Concept	% Oppose	% Unsure	% Support	Mean (1–7)	Statistical Significance
a. Continued on-site storage	35	32	33	3.92	
b. Several interim facilities	28	29	43	4.17	p < .0001 (each pairing)
c. Two permanent repositories	25	24	51	4.50	

storage practices and presenting them with arguments for and against those policies, respondents were given the following descriptions of three policy options[7] for managing UNF and asked to rate them on a scale of 1 (strongly oppose) to 7 (strongly support).

a. After used nuclear fuel is removed from cooling pools, continue the current practice of temporarily storing it near ground level at designated nuclear power plants in 39 states. This option does not require additional transportation of radioactive materials by train or truck, but it is not without political and legal obstacles. Some states are suing the federal government to end temporary storage practices at nuclear power plants.

b. Construct several interim storage facilities that would be easier to secure and could store used nuclear fuel safely up to a hundred years, which is longer than envisioned for current storage at nuclear power plants. Eventually, the materials would need to be moved to a permanent nuclear repository. This option initially requires transporting used nuclear fuel by train or truck over moderate distances and is likely to generate political and legal opposition.

c. Construct two large nuclear repositories (one in the western United States and one in the east) that can be most easily secured and would provide permanent storage and disposal of used nuclear fuel for thousands of years. This option requires transporting used nuclear fuel by train or truck over longer distances and is likely to generate political and legal opposition.

As shown in Table 1, the option of two permanent repositories was most favored and was the only option supported by a majority of respondents. This was followed by the interim consolidated storage facilities option; current practices were the least favored option.

Proximity to Current and Prospective Storage Facilities

The siting of a nuclear facility is typically assumed to generate "not-in-my-backyard" (NIMBY) reactions among nearby residents (Groothuis and Miller, 1994; Kraft and Clary, 1991), but in practice the relationship between proximity and public support has been more complex (Greenberg, 2009; Jenkins-Smith et al., 2011). In considering the BRC's recommendations for reliance on volunteer host communities and consent-based siting of UNF management facilities, locating proposed facilities raises at least three interrelated questions. First, what (if any) are the implications of residents' proximity to *current* temporary storage sites for supporting a national strategy of consolidating UNF at permanent repositories and interim storage facilities? Second, how does proximity to proposed *new* consolidated UNF facilities influence support for them? And third, does the experience of living near an existing UNF temporary storage site condition acceptance of future consolidated facilities near one's residence?

To explore how proximity to current storage facilities may relate to policy preferences, we first estimated the straight-line distance from the primary residence of each respondent to the nearest facility at which UNF is currently stored.[8] Estimated distances varied from 1 to 400 miles, with an average of 73.3 miles.

[7] The three options were presented in a random sequence to each respondent to avoid ordering effects.

[8] For participants who allowed their residential locations to be recorded, proximity was estimated using the most precise information available from three geolocation sources. If the equipment used to take the Web-based survey afforded exact latitude and longitude, precise geolocation was recorded; if the equipment did not provide latitude/longitude, an estimate based on IP address was used; for all others, estimated distance was based on the centroid of the respondent's zip code area.

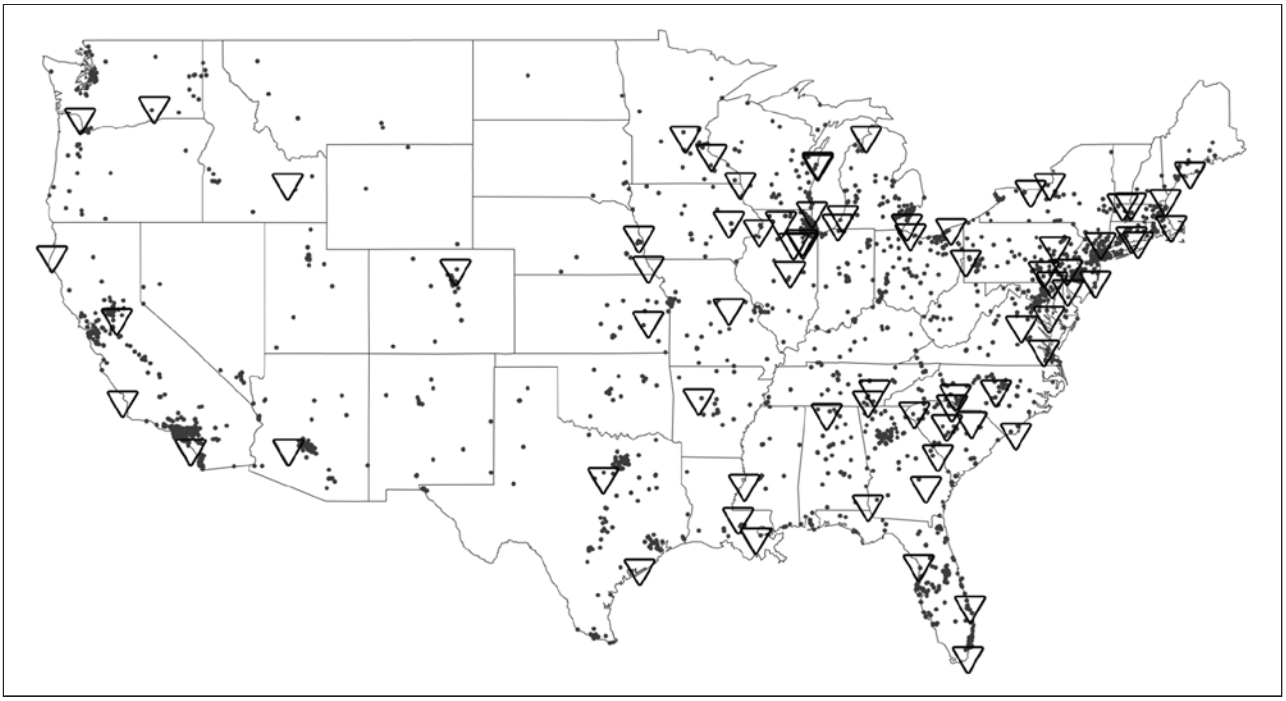

FIGURE 1 Respondents' proximity to UNF storage sites (2012).

Seventy-eight percent of respondents resided within 100 miles of a UNF storage site (by comparison, we estimate that 75.5 percent of the U.S. population resides within 100 miles of a licensed UNF storage facility).[9]

Figure 1 shows the sites at which UNF is currently stored in cooling pools or dry casks, and the locations of the primary residences of the 1,715 survey respondents who consented to provide their residential location information. The figure shows the widespread dispersal of UNF and the proximity of those locations to population densities.

Does proximity to current temporary storage sites of UNF influence public support for the general strategy of UNF management recommended by the BRC? To address this question, we first randomly divided respondents into two equal subsamples. Both groups were then told to assume the following:

GROUP A: Assume that construction of two underground mine-like repositories is being considered for long-term storage and disposal of used nuclear fuel. One would be in the eastern United States and the other in the west. Each of these sites would include secure surface buildings and a mine deep underground where radioactive materials could be isolated from people and the environment, and [the mine] could be designed [either] to allow retrieval or to permanently seal away the materials. The facilities and the mines would be designed to meet all technical and safety requirements set by the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, and state regulatory agencies.

GROUP B: Assume that construction of one or more interim above-ground storage facilities is being considered where used nuclear fuel could be stored safely for up to a hundred years. Each of these sites would include secure surface facilities where used nuclear fuel could be consolidated and stored, and where the radioactive materials could cool and be prepared and packaged for later shipment to a permanent repository. These interim storage facilities would be designed to meet all technical and safety requirements set by the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, and state regulatory agencies.

Each group was then asked to indicate support for the policy on a scale of 1 (strongly oppose) to 7 (strongly support).

[9] Estimates of population proximity to UNF storage sites are based on the Census Bureau's Zip Code Tabulation Areas (ZCTAs), using 2010 census data and including all ages/races and both genders. The Census Bureau calculates an area-weighted average point inside each ZCTA polygon, and publishes the associated latitude/longitude (similar to the centroid of a postal zip code area). We used these ZCTA center points to measure distances to the UNF licensed storage sites, as shown in the map in Figure 1. Based on the ZCTA population data and center points, we then calculated the percentages of the population of the contiguous 48 states that reside at varying distances from the nearest licensed UNF storage site.

TABLE 2 Mean Support for Future UNF Facilities by Proximity (2012)

Mean Support (1–7)	No Proximity Specified	300 Miles from Residence	100 Miles from Residence	50 Miles from Residence
Permanent repositories	4.65	4.35	4.00	3.60
Interim storage facilities	4.29	4.25	3.87	3.74

Using ordinary least-squares (OLS) regression, with estimated proximity to current temporary UNF storage sites as the independent variable and support for each option as the dependent variable, we found that support for permanent repositories or consolidated interim storage sites (although favored over current practices) was not systematically related to the respondent's proximity to licensed UNF storage facilities.[10] These results indicate that the distance of one's residence from a current UNF storage site is not systematically predictive of a general preference for a national strategy for the future management of UNF.

To find out whether proximity to a proposed interim storage facility or permanent repository influences support for that facility, we asked respondents to express their level of support for the same two policy options if one of the new facilities were located within one of three randomly assigned distances—300 miles, 100 miles, or 50 miles—from their primary residence.[11] Table 2 compares mean support for a permanent repository and interim storage facilities (1) with no assumptions about proximity and (2) with progressive proximity to the respondent's home.

When proximity to a respondent's primary residence was not taken into account, mean support for two mine-like permanent repositories was significantly higher than for one or more interim storage facilities ($p < .0001$).[12] When told to assume increasingly proximate locations to the respondent's primary residence, support for each option declined significantly. Mean support for repositories decreased about 23 percent for those living within 50 miles of the proposed facility ($p < .0001$), and mean support for interim storage facilities decreased about 14 percent at the same distance ($p < .0001$). Thus, although proximity to current on-site storage is not systematically related to preferences for consolidated management options for UNF, when considering how to site consolidated facilities, support can initially be expected to be negatively related to proximity to the proposed new sites—at least in a hypothetical scenario.

However, experience in siting the Waste Isolation Pilot Plant (WIPP)[13] in southern New Mexico revealed nonlinear variation in support relative to proximity. In this case, the strongest support was in the localized zone of greatest perceived benefits, such as jobs, economic gains, and improved transportation routes and emergency response capabilities (Jenkins-Smith et al., 2011).

The answer to our third question—does living close to a *current* UNF storage site condition willingness to accept prospective *new* consolidated storage and disposal facilities relative to one's primary residence—shows that proximity cannot be easily relegated to predictable NIMBY assumptions or "locally unwanted land use" (so-called LULU) concerns. For this question, we divided survey participants into groups, one composed of those who had been shown[14] that their principal residences were located within 25 miles of temporary UNF storage facilities and a second group of those who were shown that their residences were more than 25 miles from such a facility.[15] These two groups were compared with members of a third group who were not given any

[10] We also considered non-linear relationships, modeled as polynomial regressions. These estimated functional forms were not significant.

[11] The wording was as follows: "What would your level of support be if you learned that one of these [permanent repositories for used nuclear fuel (50%) / interim storage facilities for used nuclear fuel (50%)] is to be located [randomly assigned: 300, 100, 50] miles from your principal residence?" Responses were provided on a scale of 1 (strongly oppose) to 7 (strongly support).

[12] The BRC based its recommendations on permanent repositories and consolidated interim storage facilities being complementary, not alternative choices. Our study was to determine support for each independently.

[13] Operational since 1999, the Waste Isolation Pilot Plant outside Carlsbad, New Mexico, is a disposal site for defense-related transuranic radioactive waste.

[14] A random subset of 75 percent of the survey respondents received the following statement: "Based on the location information you provided, we estimate that your primary residence is approximately [insert estimate] miles (straight line) from the nearest nuclear energy facility where used nuclear fuel is currently in temporary storage. (Our estimate could be wrong, but you can check by looking at this map [a link was provided] showing where used nuclear fuel currently is being stored in the U.S.)"

[15] Distances were calculated for all respondents as described above in footnote 8, and a randomly selected subgroup (75 percent) of respondents were told how far their principal residences were (in linear miles) from an existing UNF storage facility and offered a link to a national map showing those locations. The remaining 25 percent were not told the distance or provided with the link to the map.

TABLE 3 Effects of Proximity to Current UNF Storage on Support for a Future Permanent Repository

Distance from Residence to Nearest *Current* UNF Storage Facility	Support for Repository to be Located 50 Miles from Residence	Support for Repository to be Located 100 Miles from Residence	Support for Repository to be Located 300 Miles from Residence
Shown to be within 25 miles	3.89	4.79	4.71
Shown to be over 25 miles	3.56	3.90	4.33
Distance not shown	3.55	3.96	4.26
Model *F* statistic significance	*not significant*	$p = 0.01$	*not significant*
Sample size	330	311	367

TABLE 4 Effects of Proximity to Current UNF Storage on Support for a Future Consolidated Interim Storage Facility

Distance from Residence to Nearest *Current* UNF Storage Facility	Support for Interim Storage to be Located 50 Miles from Residence	Support for Interim Storage to be Located 100 Miles from Residence	Support for Interim Storage to be Located 300 Miles from Residence
Shown to be within 25 miles	4.34	4.12	4.22
Shown to be over 25 miles	3.71	3.97	4.30
Distance not shown	3.42	3.49	4.13
Model *F* statistic significance	$p = 0.02$	$p = 0.09$	*not significant*
Sample size	289	344	366

information about the proximity of their residences to an existing UNF storage facility. Tables 3 and 4 show the average levels of support for siting a permanent UNF repository (or a consolidated interim storage facility) within 50, 100, and 300 miles of respondents' principal residences.

Tables 3 and 4 provide modest evidence that people were slightly more willing to accept new UNF facilities *if they had been informed that they currently reside within 25 miles* of an existing UNF storage site. If the proposed new facility was to be a permanent repository (Table 3), those who had been shown that they lived within 25 miles of UNF reported nominally greater support than those who either lived more than 25 miles from a site or had not been informed of their distance from a site. The increase in support was statistically significant when the new repository was to be 100 miles distant. Note that the level of support of those who were *not informed* of their proximity is very similar to that of respondents living more than 25 miles from existing UNF storage sites. Similar results were shown for a prospective siting of a consolidated interim storage facility (Table 4), with the exception that support for the new facility appears to increase among respondents informed of proximity (regardless of distance) from existing UNF storage sites.

Based on these results, we concluded that proximity to current and future UNF facilities and the siting of a new facility is a complex relationship that does not easily lead to straightforward NIMBY responses. In fact, the effects of proximity can be subtle, subject to conditioning, and nonlinear.

However, our data do suggest that residents of potential host communities who have no experience of living near a UNF storage site may be less receptive than residents of candidate sites who have lived near such facilities. Thus, our analysis indicates that knowledge of existing storage sites and the proximity of those sites to the potential host community have systematic effects on receptiveness to new UNF facilities.

Institutional Credibility and Perceived Biases in Risk Assessment

The BRC was particularly attentive to issues of institutional credibility and trust, as was noted in the final BRC report (BRC, 2012, p. x):

> The overall record of DOE and of the federal government as a whole . . . has not inspired widespread confidence or trust in our nation's nuclear waste management program. For this and other reasons, the Commission concludes that a new, single-purpose organization is needed to provide the stability, focus, and credibility that are essential to get the waste program back on track.

In general, for policies for which public support depends heavily on assessments of the risks associated with alternative strategies and designs, public trust in institutional risk evaluations and perceptions of institutional bias weigh heavily in the consideration of alternative policies. The management of UNF is particularly sensitive to the credibility of official risk assessments and projections over very long periods of time for facility concepts, functional designs, operational safety and security, and transportation of radioactive materials.

How does the public assessment of trust in institutions involved with UNF management compare with the model suggested in the BRC final report? To find out, we posed the following question:

> Managing used nuclear fuel can be technically complex, and getting information you can trust is important. Please indicate your level of trust in information provided by science and engineering experts from each of the following organizations using a scale from zero to ten, where zero means *no trust* and ten means *complete trust*. [random order]
>
> a. The U.S. Nuclear Regulatory Commission (NRC)
>
> b. The U.S. Environmental Protection Agency (EPA)
>
> c. U.S. national laboratories for energy and security
>
> d. The National Academy of Sciences (NAS)
>
> e. State regulatory agencies
>
> f. Environmental advocacy groups, such as the Natural Resources Defense Council or the Sierra Club
>
> g. The Nuclear Energy Institute (NEI), which represents the nuclear power industry
>
> h. Utility companies that own nuclear power plants
>
> i. The U.S. Department of Energy (DOE)
>
> j. A private company chartered by the government and funded by fees from nuclear energy that is given responsibility for managing used nuclear fuel from U.S. nuclear power plants[16]

After participants had rated their level of trust in each specified source of risk information, we asked the following question about expected risk bias for the same entities:

> Now we want to know more about impressions you may have about how these organizations are likely to assess risks associated with managing used nuclear fuel. Using a scale from one to seven, where one means the organization is likely to *downplay* risks, four means the organization is likely to *accurately assess* risks, and seven means the organization is likely to *exaggerate* risks, please rate your impressions of how each organization is likely to assess risks. [random order]

In Figure 2 we compare mean levels of trust in risk assessments by scientific and engineering experts from each of the organizations. Figure 3 shows mean expectations of institutional bias. The National Academy of Sciences and U.S. national laboratories for energy and security were most trusted, but the EPA, NRC, and DOE were also considered to be generally reliable sources of risk information. Risk assessments by nuclear utility companies and a prospective company chartered by the government and tasked with managing UNF policies ("Fedcorp") were seen as less trustworthy.

Several implications can be drawn from Figures 2 and 3. Because the concept of a Fedcorp is not yet a factor in public discussions, the responses shown here reflect only an initial impression based on a thumbnail characterization. We expect that variations in this characterization will influence the level of trust, and we plan to examine that issue in future studies. Nevertheless, indications are that the public will have to be persuaded that such an entity can be trusted to provide balanced information and unbiased risk assessments.

Interestingly, our sample also suggests that the broader public grants DOE a level of trust about mid-range among the key players, slightly below the level granted to EPA and NRC, but higher than the level for environmental interest groups, state regulatory agencies, and nuclear utilities. DOE, along with the National Laboratories, NRC, and state regulators, was perceived to err

[16] The BRC recommended the formation of a new single-purpose government-chartered private company outside DOE to oversee UNF policy management; we call this organization "Fedcorp" for ease of reference.

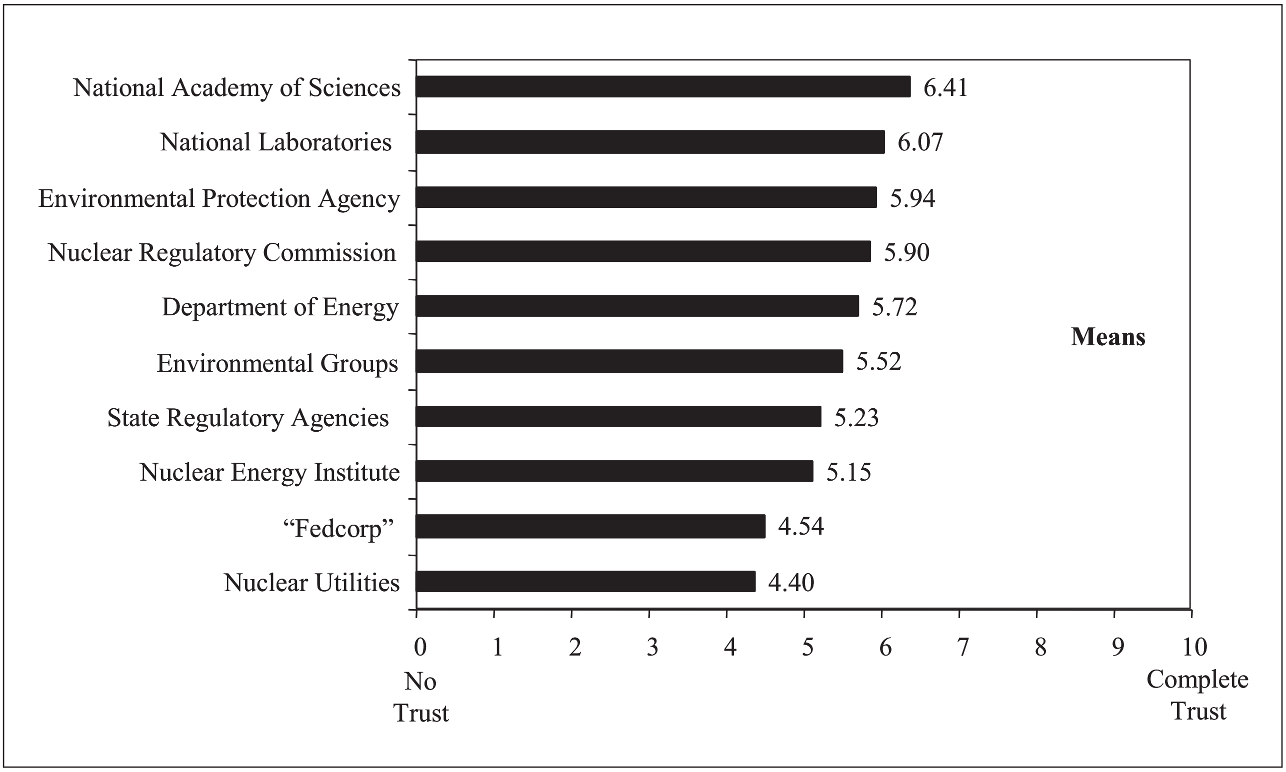

FIGURE 2 Mean levels of trust in institutional risk assessments regarding UNF (2012).

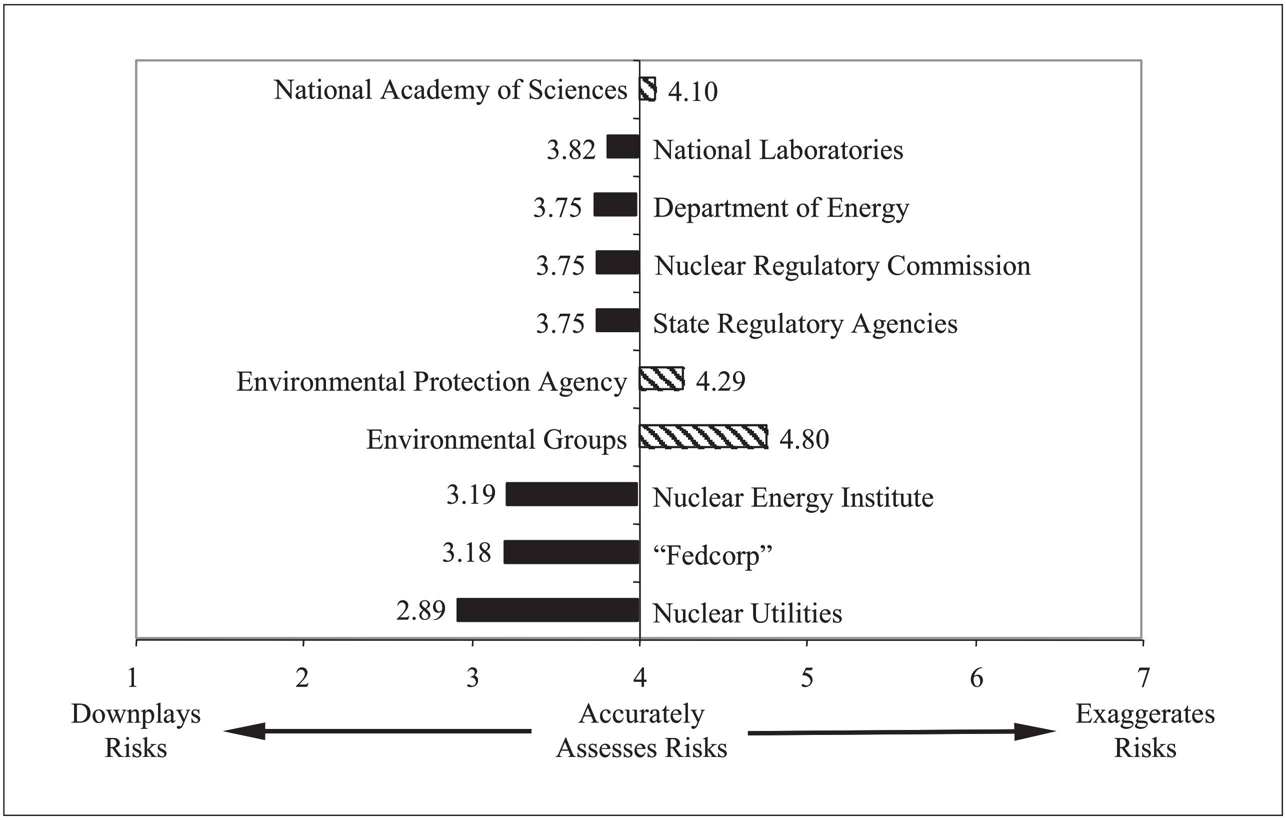

FIGURE 3 Mean levels of perceived bias in institutional risk assessments (2012).

slightly in the direction of understating risks from UNF, whereas EPA was perceived to overstate them.

As a group, however, the government labs and agencies were seen to be more credible and balanced than nongovernmental groups. In short, our sample suggests that, although the U.S. public harbors a degree of skepticism about all of the entities involved in UNF management, it retains a non-trivial reservoir of trust in the public agencies charged with managing UNF.

Public Conceptions of "Consent"

Among the key recommendations of the BRC, one of the most significant departures from prior UNF management policies is a call for a "consent-based siting process." As noted in the report, the change raises important issues about how to define and register "consent" in the policy process. First, what constitutes consent? Second, who should have the authority to grant or withhold consent? Finally, once consent has been legally given, may it be withdrawn and, if so, at what stages of the siting process?

Survey respondents consider the host state's consent an important requisite in decisions about siting UNF storage.

The BRC addressed the nature of consent only in general terms, considering the specific processes to be part of the negotiations with potential host communities. Although no formal definition was recommended, the Commission essentially considered consent a function of willingness on the part of authorized entities to enter into legal agreements (BRC, 2012, p. 57):

> The Commission takes the view that the question of how to determine consent ultimately has to be answered by a potential host jurisdiction, using whatever means and timing it sees fit. We believe that a good gauge of consent would be the willingness of the host state (and other affected units of government, as appropriate) to enter into legally binding agreements with the facility operator, where these agreements enable states, tribes, or communities to have confidence that they can protect the interests of their citizens.

To explore the issue of consent with our survey participants, we first asked them to rate the importance (0 = not at all important to 10 = extremely important) of the requirement that key stakeholders grant consent before a UNF facility can be sited. Not surprisingly, the mean response was 7.55, confirming that most respondents considered the host's consent an important requisite.

We then defined two broad approaches to obtaining consent, differentiated by the degree of public involvement, and asked which approach was preferred. The two descriptions shown below were presented in random order. Each respondent's home state was inserted where indicated to personalize the question.

> A: "Consent" should involve a process where many different stakeholders must agree. Thus consent should require agreement by local elected officials, [insert state]'s governor, both of [insert state]'s U.S. senators, the U.S. congressperson representing the host community, and [insert state]'s environmental protection agencies. In addition, a state-wide vote should be held that wins the support of a majority of citizens in [insert state].

> B: "Consent" should involve a process where only those that are most affected must agree. Thus consent should require agreement by local elected officials and [insert state]'s governor. In addition, a vote should be held that wins the support of a majority of the residents in the local host community.

The more inclusive process (A) was preferred by a modest majority (58 percent) of respondents.

Because the nature of consent is potentially negotiable with prospective hosts of UNF facilities, another way of investigating public views on the subject is to ask ordinary citizens who they think should be allowed to block/veto a decision to site a UNF facility. We presented a randomly ordered list of the entities shown in Table 5 and asked participants to select all of those they thought should be allowed to block/veto construction of a UNF facility in their state. Again, the name of each respondent's home state was inserted where indicated.

Only three entities received a majority of preferences for holding veto power: (1) a majority of citizens residing within 50 miles of the proposed facility, (2) a majority of voters in the state, and (3) the governor of the state. So, although most respondents preferred an inclusive siting process, preferences for granting authority to block a siting process were restricted to those most directly affected and the chief executive of the state.

Finally, we also gained some insight into when, in the course of the siting process, consent might be withdrawn. For this exercise, we divided the siting process into five stages, each of which was described briefly. We then asked whether a host state and local community should be allowed to withdraw consent at each stage in the process; response options were "no" or "yes."

Half of the participants were given descriptions specifying a permanent repository, and half descriptions specifying an interim storage site. The steps in the siting process were the same for both groups. We provided the introduction and five steps as shown below:

TABLE 5 Who Should Be Allowed to Block/Veto a Siting Decision (2012)

	% YES
A majority of the citizens residing within 50 miles of the proposed facilities	68
A majority of the voters of [insert state]	57
The governor of [insert state]	55
[insert state]'s environmental protection agency or its equivalent	48
The U.S. Environmental Protection Agency	40
The U.S. Nuclear Regulatory Commission	39
The U.S. Department of Energy	36
The U.S. congressperson representing the district in which the host community is located	35
Either of the two U.S. senators from [insert state]	34
The leaders of [insert state]'s legislature	29
Nongovernmental environmental groups in [insert state]	20

> A related issue involves if and when consent might be withdrawn. The siting process will proceed in stages, and at some point a final decision to build or not to build the facility must be made. Each of these stages requires considerable investment of money and time. Each stage also provides more information for making a good decision. Generally, these stages include:
>
> Stage 1: The community or state volunteers to be a candidate to host a [permanent repository/interim storage facility] for used nuclear fuel, and a technical evaluation of the site is begun. This evaluation may take several years to complete. Should the host state and local community be allowed to withdraw their consent during this stage?
>
> Stage 2: Scientific evaluation of the suitability of the site for [permanent storage and disposal/interim storage] of used nuclear fuel is completed. Should the host state and local community be allowed to withdraw their consent at this stage?
>
> Stage 3: If the site is determined to be suitable, a license to construct a [permanent repository/interim storage facility] for used nuclear fuel is submitted to the U.S. regulatory agencies; the regulatory consideration may take several years to complete. Should the host state and local community be allowed to withdraw their consent during this stage?
>
> Stage 4: If the license is provided, construction of a [permanent repository/interim storage facility] for used nuclear fuel begins. Construction will take several years to complete. Should the host state and local community be allowed to withdraw their consent during this stage?
>
> Stage 5: Construction is completed, and the [permanent repository/interim storage facility] is prepared to receive used nuclear fuel. Should the host state and local community be allowed to withdraw their consent at this stage?

The percentages of respondents indicating whether or not consent could be withdrawn at each stage, for each type of facility, are shown in Table 6.

For both types of UNF facilities, substantial majorities of respondents thought potential host communities or states should be permitted to withdraw consent at each of the first three stages, which involve site evaluation and licensing. Only about four in ten respondents would allow consent to be withdrawn during stage 4 (after a license has been issued), and only about one in three respondents would allow consent to be withdrawn once construction has been completed.

Participants wanted to preserve the option of withdrawing consent, but most thought withdrawal should not be available after a license had been provided or

TABLE 6 At What Stage in the Siting Process Should Potential Host Communities Be Permitted to Withdraw Consent?

	Permanent Repositories (% Yes)	Interim Storage (% Yes)
Stage 1: Host community/state volunteer, site assessment initiated	74.3	74.7
Stage 2: Scientific evaluation of site suitability completed	73.6	72.6
Stage 3: License application to construct a UNF facility submitted to agencies	62.2	66.2
Stage 4: License obtained, facility construction initiated	40.5	46.3
Stage 5: Construction completed, facility prepared to receive UNF	30.5	33.9

investments associated with facility construction had been made. In short, our data suggest that, although members of the public broadly support the BRC recommendation of a consent-based process for siting UNF facilities, they also prefer that withdrawal of consent be an option only in the early stages of the siting process.

Conclusions: Lessons Learned

We have focused on assessing public support for some of the key BRC policy recommendations for moving forward in managing UNF. Our investigation of public support for consent-based siting of UNF facilities yielded some valuable insights.

Storage and disposition of UNF have relatively low issue salience, and most U.S. citizens do not seek out information about current UNF management policies. When informed of current practices, and when presented with options for consolidating UNF at permanent repositories and/or interim storage facilities, both options were preferred to current temporary storage practices. However, support for permanent repositories was significantly higher than for interim storage sites. Although the BRC recommendations include strong arguments for both types of facilities, the justification for interim storage is not as evident to those whom we surveyed.

The implications of living near current and proposed UNF facilities cannot be reduced to simple assumptions about NIMBY, but preliminary evidence does suggest that living near a current temporary site may condition residents to be somewhat more accepting of facilities for consolidated storage and disposal. In addition, respondents evidenced different levels of trust in risk assessments, depending on the source, and evinced not unreasonable expectations of institutional biases.

Generating public support for a new federal corporation to site, build, and operate UNF facilities, as recommended by the BRC, may require a substantial investment in public engagement. Most participants favored more inclusive processes for determining public/official consent to the siting of UNF facilities. But they were cautious about allowing veto power to be widely dispersed, preferring to limit it to the populations most directly affected and the governor of the host state. Most indicated they would allow legal consent to be withdrawn during site evaluation and the licensing phase of the siting process, but not after licensing or the initiation of facility construction.

In summary, although more research is needed, our findings highlight some of the complexities that will be involved in conveying the BRC recommendations to the public. However, they also indicate broadly positive public assessments of the policy design principles underlying those recommendations.

Acknowledgments

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References

BRC (Blue Ribbon Commission on America's Nuclear Future). 2012. Report to the Secretary of Energy. Available online at *http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf*.

Greenberg, M. 2009. NIMBY, CLAMP, and the location of new nuclear-related facilities: U.S. national and 11 site-specific surveys. Risk Analysis 29(9): 1242–1254.

Groothuis, P., and G Miller. 1994. Locating hazardous waste facilities: The influence of NIMBY beliefs. American Journal of Economics & Sociology 53(3): 335–346.

Herron, K., H. Jenkins-Smith, and C. Silva. 2012. US Public Perspectives on Security. Sandia Report: SAND2012-0165. Albuquerque, NM: Sandia National Laboratories. Available online at *http://crcm.ou.edu/projects/nuclear/*.

Jenkins-Smith, H., C. Silva, K. Herron, S. Trousset, and R. Rechard. 2012. Enhancing acceptability and credibility of repository development for spent nuclear fuel. The Bridge 42(2): 49–58.

Jenkins-Smith, H., C. Silva, M. Nowlin, and G. deLozier. 2011. Reversing nuclear opposition: Evolving public acceptance of a permanent nuclear waste disposal facility. Risk Analysis 31(4): 629–644.

Kraft, M., and B. Clary. 1991. Citizen participation and the NIMBY syndrome: Public response to radioactive waste disposal. Western Political Quarterly 44(2): 299–328.

Three recent projects illustrate the benefits of bringing a social sciences perspective to engineering innovation.

The Value of the Social Sciences for Maximizing the Public Benefits of Engineering

Jameson M. Wetmore

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Since the early 1900s, engineering professional societies have established codes of ethics to ensure that their members maintain a high level of professionalism (Pfatteicher, 2003). The premise is that because engineers are entrusted with special knowledge, they have a duty to use that knowledge in the public interest. In their codes, these societies outlined some of those duties and shared them with the world. Since those early efforts, a number of additional strategies for defining and propagating ethical engineering have been developed, such as textbooks, courses, and even a Division of the American Society for Engineering Education dedicated to the topic (Herkert, 2000).

Many of these later efforts have focused on ensuring that engineers do no harm by calling attention to specific temptations (e.g., cutting corners, skimming a little profit off the top, or passing the buck). Ethical issues are also often presented as dilemmas about balancing the good and the bad. For instance, is it ethical to forge data to justify a decision that one knows is the right thing to do? Should one ensure a level of safety higher than is legally required? If the only way of building a water purification system in a developing country is to abide by local customs and bribe officials, should one pull out the wallet or abandon the project? Issues like these, which have been called micro-ethical questions (Herkert, 2005), are often framed as arguments against lying, cheating, or stealing by engineers.

A Broad View of Ethics

Micro-ethics continue to be at the heart of most educational programs in engineering ethics, but considerable efforts are also being made to encourage engineers to consider macro-ethical issues—issues that an individual engineer alone cannot hope to address. Examples include how much of the U.S. federal research and development budget should be spent on defense, whether engineers should be rewarded more for researching new technologies to address problems in the developing world than for finding ways of adapting existing technologies to local contexts, and how engineers can ensure that their work produces genuine human good and not just a new technological toy that satisfies a desire for change.

Many of these questions are based on a somewhat radical idea in the engineering world—new technologies do not automatically make the world a better place. Therefore, one must first ask what is best for the world and then try to find a way to achieve that goal.

Macro-ethical questions are not new. In fact, most engineering codes of ethics call on engineers not only to avoid wronging others but also to actively pursue the good. For instance, the first clause of the first part of the IEEE code of ethics states that engineers must "accept responsibility in making decisions consistent with the safety, health, and welfare of the public" (*www.ieee.org/portal/pages/iportals/aboutus/ethics/code.html*). The first fundamental principle in the ASCE code of ethics is that "engineers uphold and advance the integrity, honor and dignity of the engineering profession by . . . using their knowledge and skill for the enhancement of human welfare and the environment" (*www.asce.org/Leadership-and-Management/Ethics/Code-of-Ethics/*).

Although professional codes of ethics implore engineers to consider the broad implications of their work and the implications of the engineering profession in general, integrating these principles into engineering ethics education has been difficult for at least three reasons. First, they raise very difficult questions to which there are no simple right or wrong answers. Indeed, the profession as a whole has not settled on best responses for many macro-ethical questions.

Second, although individuals may come to their own solutions to these questions, they cannot make them a reality on their own. Effecting change on the macro-ethical level requires the concerted efforts of many engineers, and sometimes many non-engineers as well. Making the shift from individual decisions to group decisions is not a simple process.

And third, engineering ethics has been based largely on a collaboration between two disciplines—engineering and philosophy—that are not always sufficient for analyzing the issues raised by macro-ethical questions. Philosophy is useful for defining social welfare, but to develop strategies to enhance social welfare one must also collect data to determine the potential effects of engineering projects.

Gaining Perspective with Social Sciences

The three challenges posed by macro-ethical questions have led a number of experts to argue for a larger role for social sciences in discussions about engineering ethics (Johnson and Wetmore, 2009). History, sociology, anthropology, political science, and science and technology studies can all be helpful in addressing macro-ethical engineering questions because they examine how change happens, provide tools to improve our understanding of the effects of technology on the world, and provide strategies for analyzing and balancing the pros and cons of different ways of addressing complex issues.

> *New technologies do not automatically make the world a better place.*

If engineers just built widgets, social science might not be very useful. But engineers are system builders, and new technologies are successful only when they are linked with existing technologies. In addition, new bigger technological systems work only if they mesh with social systems.

One scholar has gone so far as to argue that the best engineers are "heterogeneous engineers"—that is, engineers who understand both technical and social systems and can build the two simultaneously. Only heterogeneous engineers, who consider the social consequences of their actions, are well equipped to work for the public welfare (Law, 1987).

Many senior engineers have learned to balance technical and social issues through a lifetime of practice and have achieved their success because of it. But it is pos-

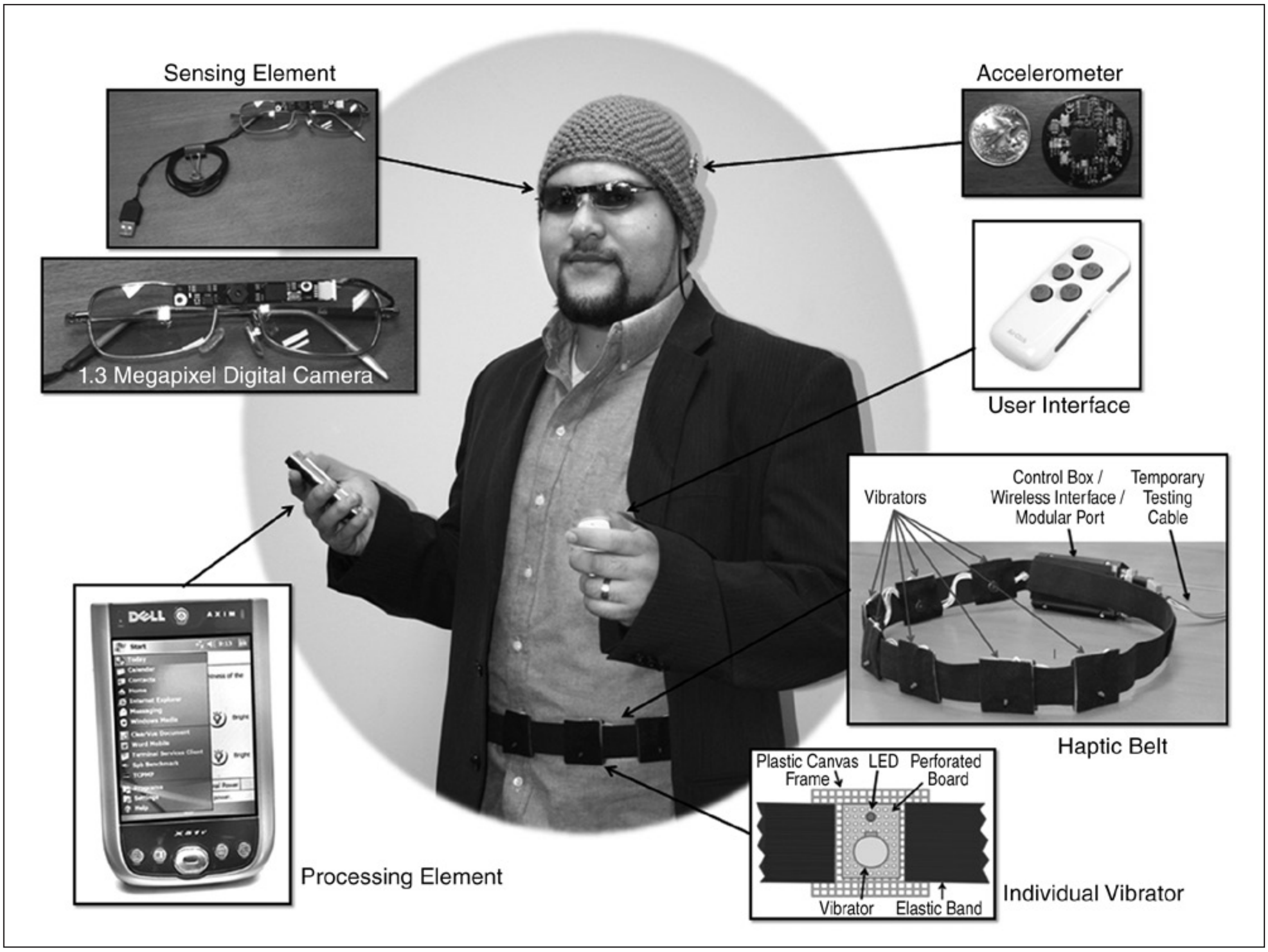

FIGURE 1 Prototype system developed by students in the Center for Cognitive Ubiquitous Computing (CUbiC) at ASU includes a camera, a face and facial-expression recognition system, and haptic interfaces to enable blind people to pick up visual cues in social and professional situations.

sible to accelerate the learning process for early-career engineers and, perhaps, teach more advanced engineers new tricks as well.

For instance, engineers can take workshops that introduce them to the basics of social science as it relates to their work. Although in most cases such workshops do not have enough time to go into much detail, even a basic understanding can provide some useful tools and, perhaps even more important, raise an engineer's awareness of what a partnership with social scientists might contribute to an engineering project. Such partnerships can range from short-term consultations to long-term collaborations in which engineers and social scientists continually learn from each other.

The following examples illustrate some of the possible outcomes of pairing engineers and social scientists. These are by no means exhaustive, but they provide an idea of how, with even a small exposure to social sciences, engineers can increase the chances that their work will contribute directly to the public welfare.

Designing for the Blind

This first example demonstrates what graduate students can accomplish with just a little training in the social sciences. The Center for Cognitive Ubiquitous Computing (CUbiC) at Arizona State University (ASU) (*cubic.asu.edu*), headed by Sethuraman Panchanathan, focuses on developing technologies to assist people with disabilities. Sreekar Krishna, a new Ph.D. candidate in the CUbiC lab, was looking for a research project in which he could use his skills as a computer scientist to help blind people. Rather than focusing on a particular technology and looking for ways to use it, Krishna and his lab colleagues began by asking a simple question: "What is needed?" (Krishna et al., 2008, p. 2). To answer this question, they used time-tested social science techniques—they put together two focus groups and followed up with a web-based survey.

Because Krishna and his colleagues had a strong background in computer-assisted vision, their first instinct was to design a way to help blind people navigate through space. However, they learned from their focus groups that blind people were already pretty adept at moving safely. What was woefully lacking, however, was a technology that could help them navigate social situations.

The blind people they worked with noted that having access to social cues (especially nonverbal visual cues) could greatly advance their careers. For instance, glancing at a watch to signal that it is time to wrap up a meeting or making eye contact to clarify the person being addressed are important forms of communication in social situations. Without access to these signals, many blind people find it difficult to manage events or collaborate with sighted individuals.

Krishna and his colleagues ultimately developed a prototype system that included a camera, a face and facial expression recognition system, and haptic interfaces that indicate to a blind person whether someone in the room is smiling, nodding, making eye contact, or conveying other unspoken social signals (Krishna, 2011). This new technology can potentially meet a need that many sighted people have never recognized. Because Krishna took the time to familiarize himself with some basic social science tools, he was able to create a technology to help blind people improve their ability to manage others and take the lead in social and professional situations.

Regulating Emerging Technologies

A second example illustrates the benefits of a short-term collaboration between social scientists and engineers. In the summer of 2007, Troy Benn, a graduate student in civil and environmental engineering at ASU, participated in "Science Outside the Lab," a two-week program offered by the ASU Consortium for Science, Policy and Outcomes, that uses U.S. federal science policy as a case study to introduce graduate students in science and engineering to the uses and social implications of technical knowledge (*www.cspo.org/outreach/scienceoutsidethelab/*). During the program Benn met with funders, lobbyists, congressional staffers, museum curators, lawyers, and historians.

In addition to learning how the federal government develops regulations for emerging technologies, Benn was conducting research on how much nanosilver comes out of antibacterial clothing when washed (Benn and Westerhoff, 2008). In discussions of his project with an official from the Environmental Protection Agency (EPA), Benn began to see how his research could help policy makers develop better regulations. He also got some training in translating technical information for non-experts. After the program ended, he kept in touch with staff at EPA and the Woodrow Wilson Center Project on Emerging Nanotechnology to keep them abreast of his latest research.

Ultimately, Benn's publications were read by numerous policy makers, and his work was cited half a dozen times in one EPA working report (EPA, 2010). By learning how knowledge is transferred in the policy realm and developing the communication skills to share his information with policy makers, Benn was able to make a significant impact on regulations to protect American consumers.

A social scientist discovered why villagers had not embraced the modern stoves developed for them.

Clean Cooking in Ghana

A third example illustrates the benefits of a long-term collaboration between a social scientist and engineers. GlobalResolve, a project of the ASU College of Technology and Innovation, works on developing sustainable technologies to provide clean water, energy, and economic development for rural communities in the developing world (*GlobalResolve.asu.edu*). The first project by GlobalResolve was to improve the health of people in a small village in Ghana by developing an ethanol-gel fuel production facility and stoves that can run on that fuel. The early prototypes were smokeless, odorless, clean, and efficient, but the villagers were not very interested in using them.

By that time, Nalini Chhetri, a scholar who specializes in international development, had joined the program. She helped conduct a mapping exercise in the village to determine why people were not excited by the stoves (Chhetri, 2009). Through the mapping exercise, the team discovered that a number of their original assumptions—many of which had not been recognized as assumptions at the time—had made the devices unworkable.

For instance, each stove was designed for a family of five, but in the village 10 to 20 family members often lived together. In addition, the dietary staple was a very thick porridge that required vigorous stirring, but the original ethanol stoves were tall and skinny and could not stabilize the pots that were traditionally used. Finally, the villagers did not understand why anyone would put forth time and effort to brew ethanol as a fuel when there was plenty of free firewood just a short walk away.

Based on this new information, Chhetri facilitated a conversation between the villagers and engineers to get a better understanding of local customs, cuisine, and interpersonal relationships. Through these discussions, the team was able to look beyond the function of the technology and develop systems that fit with existing practices as much as possible. A subsequent technology, the Twig Light, which uses embers from the fire to power a small LED light, has generated significantly more excitement among the villagers.

Proactive Pursuit of Human Welfare

None of these projects quite fits the mold of a typical engineering ethics case study, because none of them focuses on a dilemma. However, they are positive examples of how some higher goals of engineering ethics and professionalism can be achieved. At the core of each project is a desire to "enhance human welfare." By working with social scientists and using the tools they provide, engineers were able to link their technical work to positive social change.

These examples are not unique. In fact, the National Academy of Engineering (NAE) also promotes these kinds of interactions. In a keynote talk before the 2000 NAE Annual Meeting, then NAE President Wm. A. Wulf cited the work of two social science scholars—sociologist Charles Perrow (1999) and historian Ed Tenner (1997)—for inspiring him to establish a program on engineering ethics, the NAE Center for Engineering, Ethics, and Society (CEES) (Wulf, 2000). The underlying principle of the program is recognition of the need for "multi-disciplinary examinations" to address ethical and societal issues related to the development of new technologies (*nae.edu/activities/projects/cees.aspx*). CEES

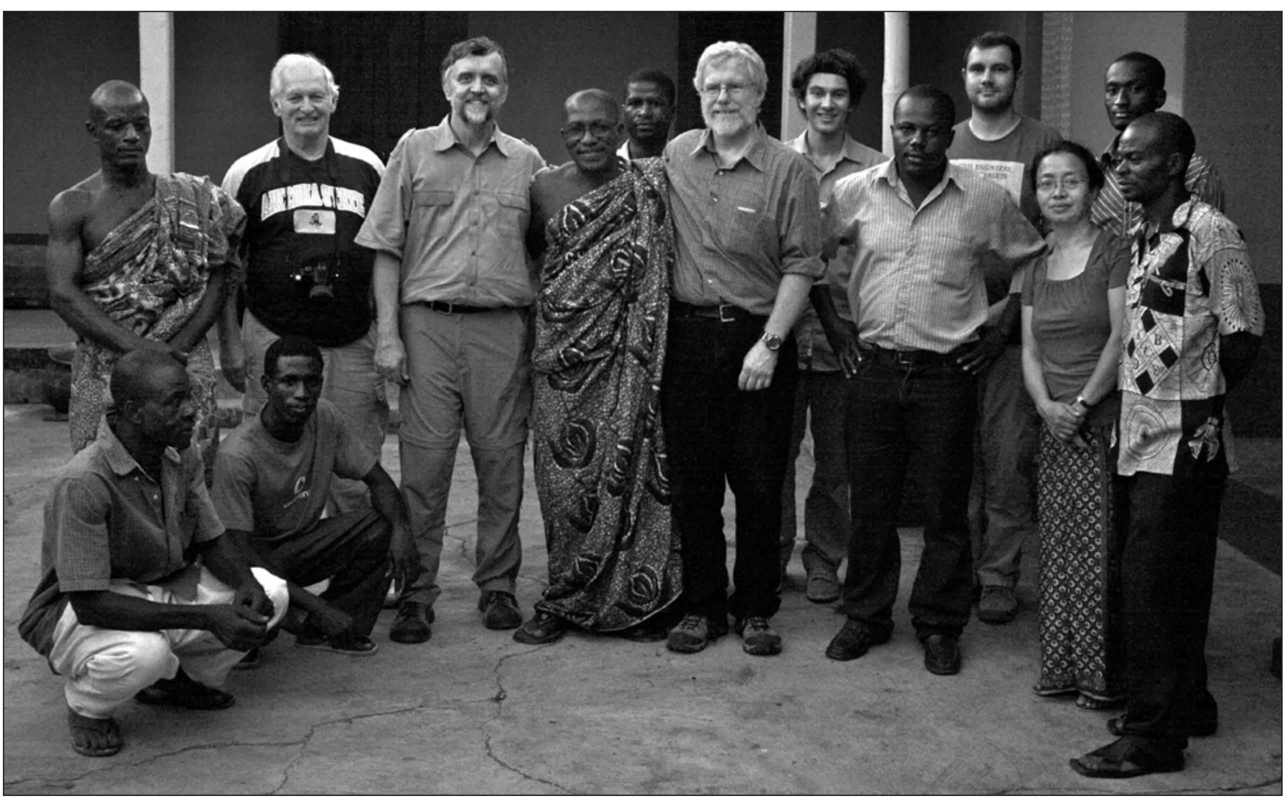

FIGURE 2 Members of the ASU GlobalResolve project in the village of Domeabra, Ghana. Social scientist Nalini Chhetri is in the front row, second from the right. Co-founder of GlobalResolve Mark Henderson is standing third from left.

now hosts workshops and projects that bring together engineers, social scientists, and others on a regular basis.

Conclusion

Most people who pursue careers in engineering want to make the world a better place. They believe technologies can ease burdens, open up new possibilities, and even bring people together. To realize those goals, they must be able to understand the world in which they work, the ways in which their technologies will affect the world, and the ways in which people will respond to their products.

There is no precise, repeatable way to achieve this understanding, but social scientists have developed a number of tools and approaches that can help technology builders determine the effects of their work. Links between engineers and social scientists can go a long way toward developing an understanding of context, visualizing where certain paths might lead, and achieving the highest goal of engineering—contributing to human welfare.

References

Benn, T.M., and P. Westerhoff. 2008. Nanoparticle silver released into water from commercially available sock fabrics. Environmental Science and Technology 42(10): 4133–4139.

Chhetri, N. 2009. Lessons from Ghana: Why some technological fixes work and others don't. CSPO Soapbox, August 27. *http://cspo.org/soapbox/*.

Herkert, J.R. 2005. Ways of thinking about and teaching microethics and macroethics in engineering. Science and Engineering Ethics 11(3): 373–385.

Herkert, J.R. 2000. Engineering ethics education in the USA: Content, pedagogy and curriculum. European Journal of Engineering Education 25(4): 303–313.

Johnson, D.G., and J.M. Wetmore. 2007. STS and ethics: Implications for engineering ethics. Pp. 567–582 in *New Handbook of Science and Technology Studies*, edited by E. Hackett, O. Amsterdamska, M. Lynch, and J. Wajcman. Cambridge, Mass.: MIT Press.

Krishna, S., D. Colbry, J. Black, V. Balasubramanian, and S. Panchanathan. 2008. A Systematic Requirements Analysis and Development of an Assistive Device to Enhance the Social Interactions of People Who Are Blind or Visually Impaired. Presentation at the Workshop on Computer Vision Applications for the Visually Impaired, Marseilles, France. Available online at *http://hal.inria.fr/inria-00325432/*.

Krishna, S. 2011. Mediated Social Interpersonal Communication: Evidence-based Understanding of Multimedia Solutions for Enriching Social Situation. PhD dissertation. Arizona State University.

Law, J. 1987. Technology and Heterogeneous Engineering: The Case of Portuguese Expansion. Pp. 111–134 in The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, edited by W.E. Bijker, T.P. Hughes, and T. Pinch. Cambridge, Mass.: MIT Press.

Perrow, C. 1999. Normal Accidents: Living with High-Risk Technologies. Princeton University Press.

Pfatteicher, S.K.A. 2003. Depending on character: ASCE shapes its first code of ethics. Journal of Professional Issues in Engineering Education and Practice 129(1): 21–31.

Tenner, E. 1997. Why Things Bite Back: Technology and the Revenge of Unintended Consequences. Vintage.

US EPA. 2010. Scientific, Technical, Research, Engineering and Modeling Support Final Report: State of the Science Literature Review: Everything Nanosilver and More, August.

Wulf, W.A. 2002. Great Achievements and Grand Challenges. The Bridge 30(3-4): 5–10.

Since the Macondo well blowout, improvements have been made in management and safety systems and in regulatory regimes.

Lessons from the Macondo Well Blowout in the Gulf of Mexico

Raymond Wassel

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Commercial deep-water drilling involves highly complex and highly risky operations. Companies must coordinate the operation of sophisticated equipment to construct wells in uncertain geologic formations, often under challenging environmental conditions. Despite the impressive capabilities of the technologies, the selection and application of technologies for constructing a particular well are subject to the unpredictability of human decision making, as they were two years ago in drilling the Macondo well in the Gulf of Mexico. The well blowout and subsequent explosions and fire on the *Deepwater Horizon* drilling rig on April 20, 2010, led to the deaths of 11 workers and at least a dozen serious injuries. It is estimated that nearly 5 million barrels of hydrocarbons were released into the gulf over a period of nearly three months after the blowout (McNutt et al., 2011).

In December 2011, the National Academy of Engineering (NAE) and National Research Council (NRC) released *Macondo Well–Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety*, a report prepared in response to a request from Secretary of the Interior Ken Salazar.[1] The authoring committee of eminent engineers and scientists found that a number of flawed decisions had led to the blowout and explosions, indicating a

[1] The final version of the report was published in 2012 and is available at *www.nap.edu/catalog.php?record_id=13273*. A list of committee members can be found in the front matter of the report.

lack of effective safety management among the companies involved in the disaster. This article provides an overview of the committee's findings and observations related to the incident and a summary of the recommendations for reducing the likelihood and effects of future well blowouts resulting from offshore drilling.

Challenges in Constructing Offshore Wells

When drilling a well into geologic formations beneath the seabed, rig personnel on the surface pump dense drilling mud into the wellbore to counteract pressure exerted by hydrocarbons or saline water in the pore space of the rocks (referred to as pore pressure). If the pressure exerted by the drilling mud is lower than the pore pressure, fluids may flow into the wellbore (an event known as a "kick"). If the kick is not brought under control, a well blowout can occur.

Because pore pressure usually increases with drilling depth, increases in mud weight may be necessary to prevent kicks as the well is drilled. However, if the pressure exerted by the drilling mud in the wellbore becomes too great, it can cause a fracture in the exposed rock at any point in the wellbore. Drilling mud would then flow from the wellbore into the fracture and could no longer exert sufficient pressure to prevent an influx of reservoir fluids. Like pore pressure, the pressure at which a fracture occurs usually increases with drilling depth, although actual pressures can be either higher or lower than anticipated (Bommer, 2008; Maclachlan, 2007; Zoback, 2010).

If drilling mud alone cannot prevent fluids from entering the well, the rig crew installs steel casing into the wellbore and pumps a cement slurry into the casing. The slurry flows into the annular space outside the casing to seal the bottom portion so fluids from the geologic formations cannot flow up the annulus. Once the cement hardens, the weaker formations above the end of the casing will not be exposed to higher pressures from denser drilling mud as the well is drilled deeper.

If a sufficient amount of hydrocarbons is found and assessments have been completed, exploratory wells are readied for temporary abandonment, typically by sealing them with cemented liners or casings to ensure that there is no hydrocarbon flow. Plugs are also used to provide additional barriers to hydrocarbon flow. Temporary abandonment is a standard practice that allows the operating company to use the expensive drilling rig for activities elsewhere and time to install the infrastructure necessary to transport recovered hydrocarbons to shore.

The Macondo Well

In 2008, BP obtained a 10-year lease to explore and develop a part of the Mississippi Canyon region of the Gulf of Mexico. The lease was owned by BP (65 percent), Anadarko Petroleum (25 percent), and MOEX Offshore (10 percent). The Macondo well was drilled in the leased area approximately 50 miles off the coast of Louisiana to evaluate the potential for producing hydrocarbons and to survey the geologic structures associated with the hydrocarbon reservoirs. As the operating company, BP was responsible for carrying out operations. BP had leased a rig (called *Deepwater Horizon*) from Transocean, to drill the well.

The Macondo well was drilled to a total depth of more than 18,300 feet below sea level, which included an ocean depth of more than 5,000 feet. The final section of the well passed through several reservoir zones that exhibited decreasing pore pressures with depth.

The NAE/NRC report found that a number of flawed decisions led to the blowout and explosions.

As shown in Figure 1, the pore pressure decreased from about 14.1 pounds per gallon (ppg)[2] in a saltwater-bearing reservoir to about 12.6 ppg in the deepest hydrocarbon-bearing reservoir. Therefore, the drilling mud weight had to be at least 14.1 ppg to prevent the flow of hydrocarbons from the saltwater reservoir. However, the fracture mud weight near the bottom of the Macondo well was only slightly greater than 14.2 ppg (BP, 2010). Under these conditions, there was a very small margin of safety between the fracture mud weight and the mud weight necessary to avoid flow into the well (Figure 2).

The method selected for preparing the well for temporary abandonment was to insert a long-string production casing and cement it in place; the casing extended

[2] For drilling operations, pore pressure and fracture pressure are commonly expressed as the density of a fluid in the wellbore (in units of pounds per gallon) that would be required to exert an equivalent amount of pressure.

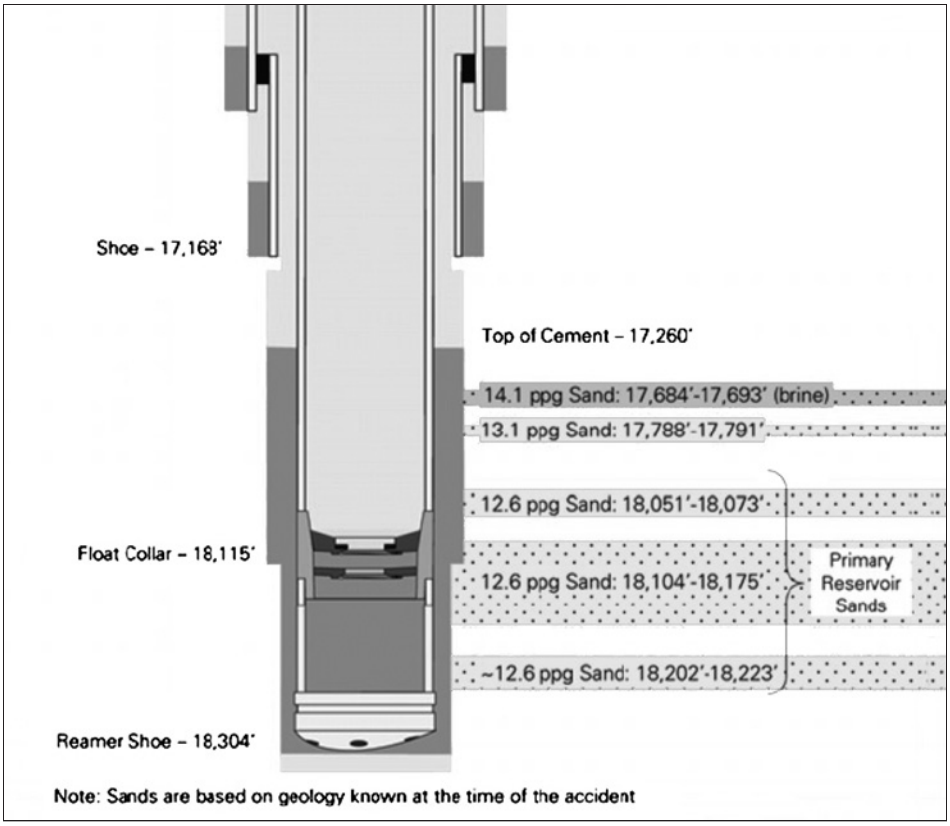


FIGURE 1 Pore pressures, expressed in pounds per gallon (ppg), in the bottom section of the Macondo well. Source: BP, 2010, p. 54. Reprinted with permission; copyright 2010, BP.

from the seafloor to the bottom of the well (BP, 2010; Transocean, 2011). In general, cementing operations are potentially problematic because, unless they are carried out properly, channels for fluid flow can form in the annular region outside the casing. In addition, if the pressure exerted by the cement slurry as it is pumped down into the well exceeds the fracture pressure, cement can flow into the fractured formation instead of remaining in the wellbore where it would eventually act as a barrier against high-pressure reservoirs.

To keep from exceeding the formation fracture pressure during the cementing process, the Macondo job was designed to pump a sequence of different slurry mixtures, which included a volume (a term of art that means a specific amount) of low-density cement between two volumes of high-density cement, one intended to fill the bottom section of the casing and one above the volume of low-density cement.

The low-density cement slurry prepared on the rig would have a density of 14.5 ppg when placed at the well bottom where conditions were about 245°F and more than 13,000 pounds of pressure per square inch (psi). To meet that specification, the slurry density was decreased to 6 ppg by adding nitrogen gas to base cement to allow for the substantial compression and heating that would occur as the foamed cement was pumped more than 18,000 feet to the bottom of the well.

The committee found that, because of the great difference in density between the two types of cement used in the pumping sequence, the heavy un-foamed cement pumped in after the foamed cement probably fell into, and perhaps through, the foamed slurry. "This would have had the unintended effect of leaving a tail slurry containing foamed cement in the shoe track at the bottom of the casing rather than leaving the heavy, un-foamed tail cement" (NAE/NRC, 2012, p. 31).

Beginning of the Hydrocarbon Flow That Led to the Blowout

After completing the cementing operation, rig personnel conducted a negative pressure test to assess the integrity of the cemented casing. This is a standard technique that involves intentionally reducing the pressure exerted by drilling mud inside the well to a point below the reservoir pore pressure by displacing some of the drilling mud with less-dense seawater. If the cement has formed an effective barrier, there will be no inflow or pressure buildup during the test.

Several of the negative pressure tests performed on the Macondo well had inconclusive and confusing results (BP, 2010; Transocean, 2011). Nevertheless, even though the negative pressure tests did not demonstrate the integrity of the cement job, rig personnel interpreted the results as indicating that the barriers were effective and proceeded with the temporary abandonment process by continuing to displace the drilling mud with seawater. The report committee concluded, "This was but one of a series of questionable decisions in the days preceding the blowout that had the effect of reducing the margins of safety and that evidenced a lack of safety-driven decision making" (NAE/NRC, 2012, p. 27).

Because the cement and mechanical barriers did not have sufficient integrity, hydrocarbons began to flow into the well. However, personnel on the *Deepwater Horizon* did not detect the flow until approximately 9:40 p.m., when mud was observed flowing uncontrolled onto the rig floor. At that point, actions were taken to reestablish control over the well, but they were unsuccessful. Flammable gas alarms on the rig sounded at approximately 9:47, followed by two explosions at approximately 9:49 and then a massive fire.

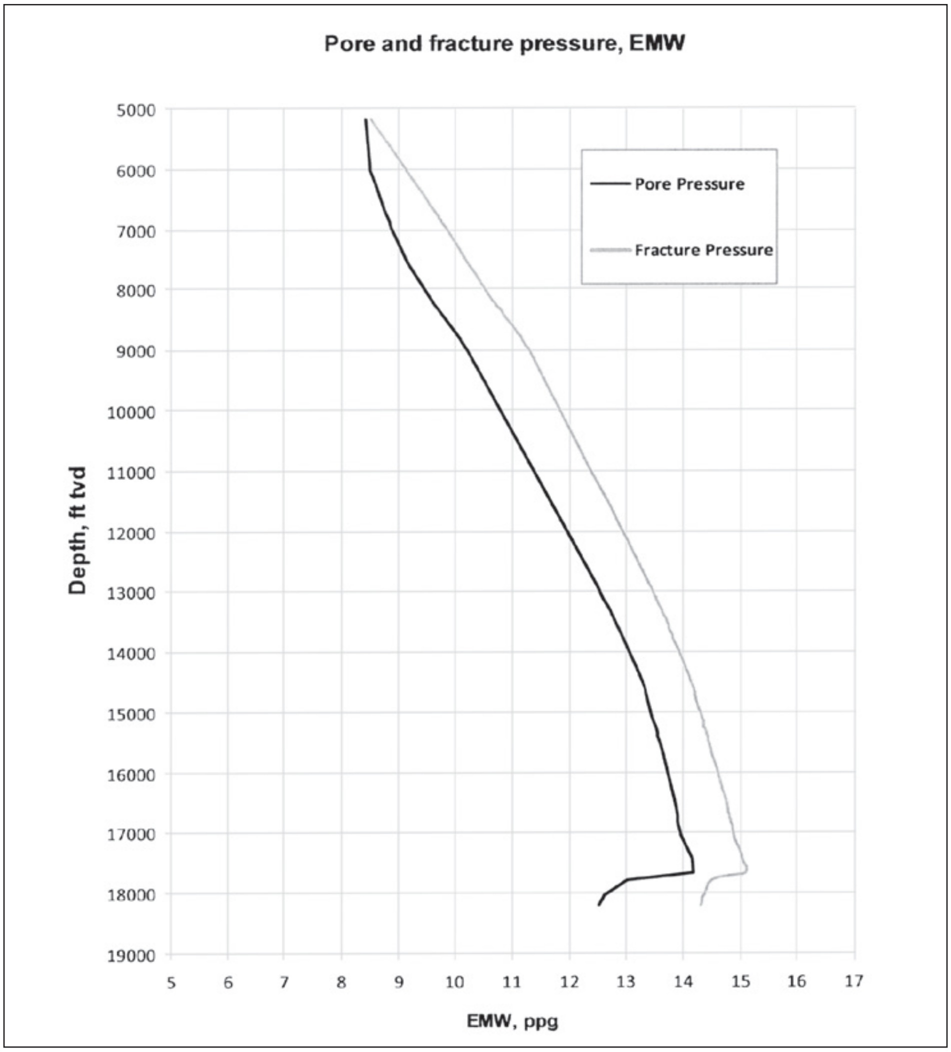


FIGURE 2 Equivalent mud window (EMW) expressed in pounds per gallon (ppg) for the Macondo well. The two curves represent pore pressure (left) and fracture gradients (right) in the shale and sands associated with the well. Values on the y-axis correspond to depths below sea level. Mud weight used by the drilling crew must be higher than the pore pressure to prevent hydrocarbon flow into the well and lower than the fracture gradient to prevent hydraulic fracturing of the exposed rock. At depths around 18,000 feet, the figure shows a small difference between the values. Source: BP, 2010, Appendix W, page 14. *www.bp.com/sectiongenericarticle.do?categoryId=9040069&contentId=7067574.*

Blowout Preventer System

The blowout preventer (BOP) system is intended to control a well if hydrocarbons unintentionally flow beyond the primary barriers during drilling or other operations. The system can be activated from the rig to seal an open wellbore, close the annular portion of the well around the drill pipe or casing, or cut through the drill pipe and then seal the well.

The BOP system for the *Deepwater Horizon* (Figure 3) was located at the wellhead on the seafloor. A riser pipe extended from the top of the system to the rig platform so that drilling fluids could circulate between the well and the rig. The uppermost of the five rams of the BOP stack was a blind shear ram (BSR) (see lower half of illustration in Figure 3). The BOP system also had an emergency disconnect system that would enable the rig to move away from the well after the BSR was activated.

As a last resort in a hierarchy of well-control strategies, the two opposing blades of the BSR were designed to slice through the drill pipe and seal the well.[3] At the time of the Macondo blowout, rig personnel could not regain control of the well by using the BOP because the BSR did not cut the drill pipe and seal the well. In

[3] One of the BSR blades had a straight edge; the other was V-shaped. This design is considered to provide inferior shearing performance compared to a configuration with two V-shaped edges (West Engineering Services, Inc., 2004).

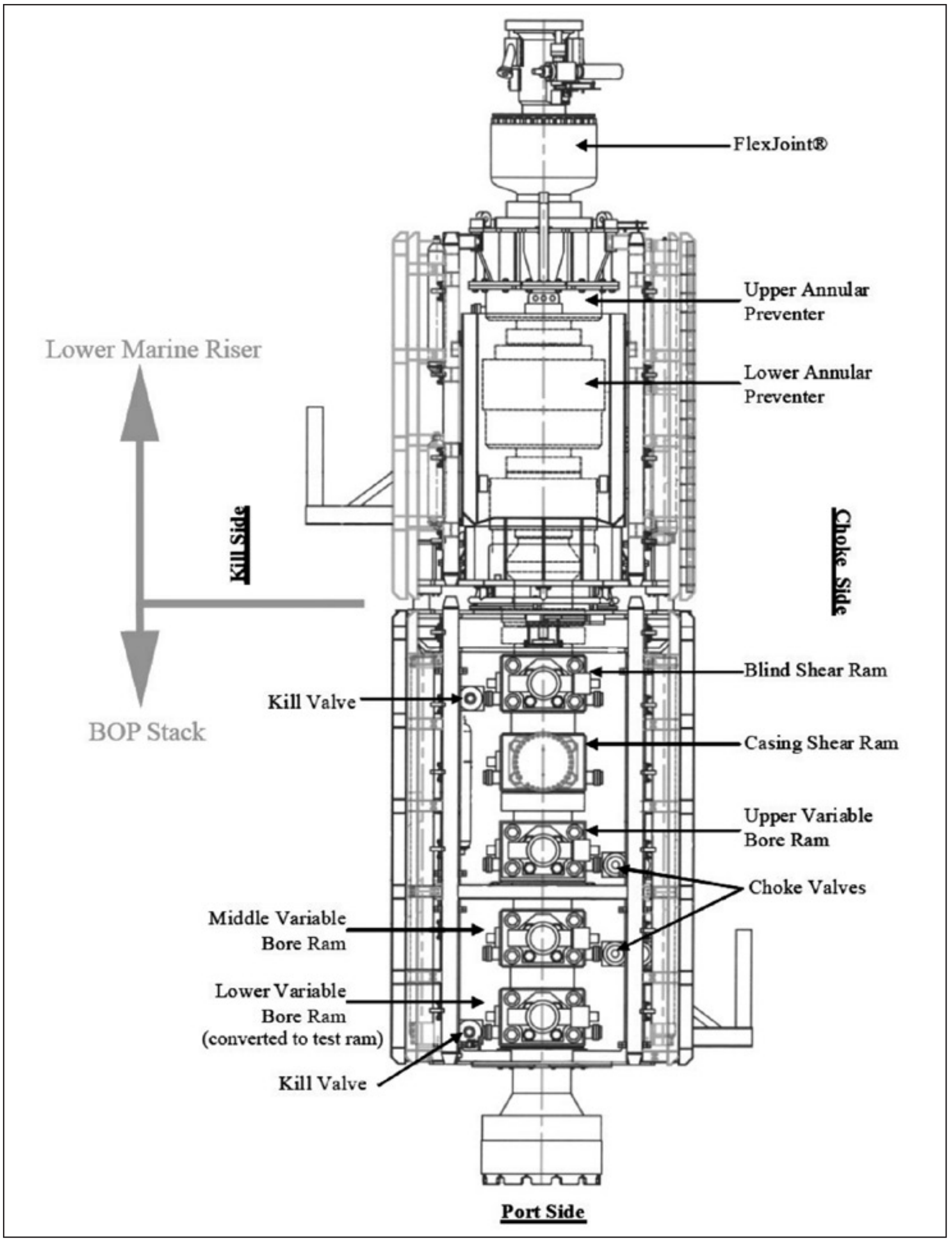


FIGURE 3 Schematic diagram of the *Deepwater Horizon* blowout preventer (BOP). See text for description. Source: DNV, 2011, Vol. I, p. 14. Reprinted with permission; copyright 2011, DNV.

addition, the emergency-disconnect system failed to separate the *Deepwater Horizon* from the well. "The BOP system was neither designed nor tested for the dynamic conditions that most likely existed at the time that attempts were made to recapture well control. Furthermore, the design, test, operation, and maintenance of the BOP system were not consistent with a high-reliability, fail-safe device" (NAE/NRC, 2012, p. 71).

The committee also found that although regulations were in place requiring recurrent testing of BOP systems, the testing was not required under conditions that simulated the hydrostatic pressures at which the BOPs were expected to function, or under dynamic flow conditions that could entrain rocks, sand, and cement, thus making cutting a drill pipe more difficult (NAE/NRC, 2012, p. 71).

Nevertheless, there were numerous warnings about potential failures of BOP systems in use prior to the Macondo blowout in reports commissioned by industry operators and regulatory organizations (e.g., West Engineering Services, Inc., 2002, 2004). According to the NAE/NRC committee, "It appears that there was a misplaced trust by responsible government authorities and many industry leaders in the ability of the BOP to act as a fail-safe mechanism" (NAE/NRC, 2012, p. 52).

Industry Management of Offshore Drilling

Companies that conduct offshore drilling operations in the United States assemble a team that includes drilling contractors, service companies, and consultants, each of whom contributes a different type of technical expertise. This complex structure and division of expertise presents a challenge to management in the oil and gas industry, which must conduct an integrated assessment of the margins of safety for a complex well such as Macondo. Various investigations have found that technical failures that occurred while drilling the Macondo well can be traced to inadequate management processes (BOEMRE, 2011; Chief Counsel, 2011; DHSG, 2011; National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling, 2011; USCG, 2011).

Based on presentations by industry representatives, the NAE/NRC committee observed that companies involved in offshore drilling tend not to use a comprehensive systems approach for addressing the many safety aspects associated with their operations. One indicator of the lack of an overall systems approach is the limited amount of system safety training provided to personnel (NAE/NRC, 2012, p. 96).

The NAE/NRC report committee found that the actions, policies, and procedures of the companies involved with the Macondo well–*Deepwater Horizon* disaster did not provide an effective systems approach to safety commensurate with the risks of the well-drilling operation. The lack of a strong safety culture is evident in the multiple flawed decisions that led to the blowout. As the committee stated, "industry management involved failed to appreciate or plan for the safety challenges presented by the Macondo well (NAE/NRC, 2012, p. 101).

Regulation of Offshore Drilling

The Minerals Management Service (MMS) of the U.S. Department of the Interior, the lead regulator at the time of the Macondo blowout, approved the exploration plans for the lease, applications for the permit to drill the well, and subsequent changes to the well drilling plan listed in modifications submitted by BP. The general approach used by MMS for the regulation of offshore drilling was largely prescriptive, that is, the agency developed specific requirements for equipment and procedures and then audited drilling operations to assess compliance with those requirements.

However, using this approach, MMS was unable to keep up with the rapid technological advances in the past few decades that had enabled a large increase in deep-water drilling in the Gulf of Mexico. The agency's problems were exacerbated by stagnant or decreasing levels of funding and technical staffing over that same period (National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling, 2011).

The NAE/NRC committee found that MMS did not comprehensively assess the risks presented by the well-drilling operation for the Macondo well: "The actions of the regulators did not display an awareness of the risks or the very narrow margins of safety" (NAE/NRC, 2012, p. 113). A rigorous review of test data from the Macondo drilling operation may have revealed that the barriers within the well had not adequately isolated hydrocarbon-bearing formations from the wellbore.

The Macondo well blowout demonstrated the need for a proactive approach to offshore drilling in U.S. waters that integrates all aspects of operations that could affect occupational and system safety (see Leveson, 2011; Rasmussen, 1997; and Rasmussen and Svedung, 2000, for discussions of systems safety). The U.S. Department of the Interior has taken an important first step in that regard by instituting safety and environmental management systems (SEMS) in 30 CFR 250 (*Federal Register*, Vol. 75, No. 199, Oct. 15, 2010). However, there is still a long way to go before the regulatory system for offshore drilling in the United States achieves the necessary capabilities.

The companies involved did not provide an effective systems approach to safety commensurate with the risks of the operation.

Improving Safety for Offshore Drilling

The committee developed recommendations for industry and regulators, identifying measures that would decrease the likelihood and mitigate the effects of future blowouts. The following paragraphs summarize the committee's major recommendations.

Because operating companies are the only ones that can view and control all aspects of well integrity, they should have ultimate responsibility and accountability for well design and well construction, as well as for assessing the suitability of the drilling rig and safety equipment. The contractor, who is hired by the operating company to drill the well, should be held responsible and accountable for the safe operation of the offshore equipment. The companies that share an offshore drilling lease should ensure that the operating company conducts activities in a way that keeps risk as low as is reasonably practicable.

As drilling operations are carried out and wells are made ready for temporary abandonment, there are safety-critical points (e.g., determining the integrity of cemented barriers placed in the well) at which poor decisions are likely to increase hazards. Guidelines should be established for incorporating adequate margins of safety into the operating company's approach to well design.

To improve regulatory effectiveness, the SEMS regulatory program should be expanded to a goal-oriented risk management system that incorporates explicit regulatory review and approval of the safety-critical points in the drilling operation. As offshore drilling operations proceed into deeper waters, the Bureau of Safety and Environmental Enforcement (BSEE)[4] and other regulators should identify the safety-critical points that warrant explicit regulatory review and approval before operations can proceed. BSEE should have knowledgeable personnel in place to provide meaningful reviews.

BOP systems should be redesigned, rigorously tested, and maintained to operate reliably under all foreseeable conditions in which they may be deployed. Proper training in the use of these systems in the event of an emergency is also essential. Instrumentation and expert system decision aids should be integrated into the offshore drilling unit to provide personnel with timely warnings of a loss of well control. If the warning is inhibited by personnel or not addressed quickly enough, autonomous operation of the BSRs and other safety systems on the rig should go into effect automatically.

Ensuring sufficient capabilities to mitigate the consequences of a hydrocarbon blowout is an important objective. Two initiatives (the Marine Well Containment Company and the Helix Well Containment Group) have established systems with the capability of containing an underwater well blowout in the U.S. Gulf of Mexico. Industry and other organizations should support further development of these systems.

Industry and regulators should significantly increase the formal education and training in implementing safety systems provided to offshore drilling personnel. Systems should be designed to support the anonymous reporting of safety-related incidents, and companies should investigate each report and convey lessons learned to their personnel and to other companies. Industry should also increase its R&D on improving the safety of offshore drilling (well design, equipment, human operational failures, and management approaches).

[4] In May 2010, Interior Secretary Salazar restructured MMS by reassigning its responsibilities to two newly formed bureaus. The bureau eventually named the Bureau of Safety and Environmental Enforcement (BSEE) is the federal entity now responsible for safety and environmental oversight of offshore oil and gas operations.

Conclusion

Since the Macondo well–*Deepwater Horizon* incident, some important improvements have been made in the management and safety systems used by companies engaged in offshore oil development and in the regulatory regime. We can be hopeful that these changes are not transitory but signal the beginning of a sustained effort to instill a culture of safety in the industry and government.

References

BOEMRE (Bureau of Ocean Energy Management, Regulation, and Enforcement). 2011. Report Regarding the Causes of the April 20, 2010 Macondo Well Blowout. Available online at *www.boemre.gov/pdfs/maps/dwhfinal.pdf*.

Bommer, P. 2008. A Primer of Oilwell Drilling, 7th ed. Austin: University of Texas at Austin.

BP. 2010. Deepwater Horizon. Accident Investigation Report. Available online at *www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/gom_response/STAGING/local_assets/downloads_pdfs/Deepwater_Horizon_Accident_Investigation_Report.pdf*.

Chief Counsel. 2011. Macondo: The Gulf Oil Disaster. Chief Counsel's Report, National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling. Available online at *www.oilspillcommission.gov/sites/default/files/documents/C21462-408_CCR_for_web_0.pdf*.

DHSG (*Deepwater Horizon* Study Group). 2011. Final Report on the Investigation of the Macondo Well Blowout. Available online at *http://ccrm.berkeley.edu/pdfs_papers/bea_pdfs/DHSGFinalReport-March2011-tag.pdf*.

DNV (Det Norske Veritas). 2011. Forensic Examination of Deepwater Horizon Blowout Preventer, Vols. I and II (Appendices). Final Report for U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Washington, D.C. Report No. EP030842. Available online at *www.boemre.gov/pdfs/maps/DNVReportVolI.pdf*, and *www.uscg.mil/hq/cg5/cg545/dw/exhib/DNV%20BOP%20report%20-%20Vol%202%20%282%29.pdf*.

Leveson, N.G. 2011. Engineering a Safer World: System Thinking Applied to Safety. Cambridge, Mass.: Massachusetts Institute of Technology Press.

Maclachlan, M. 2007. An Introduction to Marine Drilling. Ledbury, England: Oilfield Publications.

McNutt, M., R. Camilli, G. Guthrie, P. Hsieh, V. Labson, B. Lehr, D. Maclay, A. Ratzel, and M. Sogge. 2011. Assessment of Flow Rate Estimates for the *Deepwater Horizon* / Macondo Well Oil Spill. Flow Rate Technical Group Report to the National Incident Command, Interagency

Solutions Group, March 10. Available online at *www.doi.gov/deepwaterhorizon/loader.cfm?csModule=security/getfile&PageID=237763*.

NAE/NRC (National Academy of Engineering/National Research Council). 2012. Macondo Well–*Deepwater Horizon* Blowout: Lessons for Improving Offshore Drilling Safety. Washington, D.C.: The National Academies Press. Available online at *www.nap.edu/catalog.php?record_id=13273*.

National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling. 2011. Deep Water: The Gulf Oil Disaster and the Future of Offshore Drilling. Report to the President. Available online at *www.oilspillcommission.gov/sites/default/files/documents/DEEPWATER_ReporttothePresident_FINAL.pdf*.

Rasmussen, J. 1997. Risk management in a dynamic society: A modeling problem. Safety Science 27(2/3): 183–213.

Rasmussen, J., and I. Svedung. 2000. Proactive Risk Management in a Dynamic Society. Karlstad, Sweden: Swedish Rescue Services Agency. Available online at *https://www.msb.se/RibData/Filer/pdf/16252.pdf*.

Transocean. 2011. Macondo Well Incident. Transocean Investigation Report Vols. I and II (Appendices). Available online at *www.deepwater.com/fw/main/Public-Report-1076.html*.

USCG (U.S. Coast Guard). 2011. Report of Investigation into the Circumstances Surrounding the Explosion, Fire, Sinking and Loss of Eleven Crew Members Aboard the Mobile Offshore Drilling Unit *Deepwater Horizon* in the Gulf of Mexico April 20–22, 2010, Vol. I. Available online at *https://www.hsdl.org/?view&did=6700*.

West Engineering Services, Inc. 2002. Mini Shear Study for U.S. Minerals Management Service. Requisition No. 2-1011-1003. Dec. Available online at *www.boemre.gov/tarprojects/455/Final%20Report.pdf*.

West Engineering Services, Inc. 2004. Shear Ram Capabilities Study for U.S. Minerals Management Service. Requisition No. 3-4025-1001. Sept. Available online at *www.boemre.gov/tarprojects/463/(463)%20West%20Engineering%20Final%20Report.pdf*.

Zoback, M.D. 2010. Reservoir Geomechanics. Cambridge, U.K.: Cambridge University Press.

NAE News and Notes

NAE Newsmakers

Nine NAE members were honored at the **2012 Institute of Electrical and Electronics Engineers (IEEE) Honors Ceremony** in Boston, Massachusetts, on June 30, 2012. The purpose of this annual event is to recognize technical professionals in many disciplines for exceptional achievements that have had a lasting impact on technology, society, and the engineering profession. The following NAE members were honored:

- **Mark T. Bohr**, Intel Senior Fellow, Intel Corporation, received the **IEEE Jun-Ichi Nishizawa Medal** "for sustained leadership in developing innovative transistor technologies for advanced logic products." Sponsored by the Federation of Electric Power Companies, Japan, the award is given for outstanding contributions to material and device science and technology, including practical application.
- **John B. Goodenough**, Centennial Professor of Engineering, Texas Materials Institute, University of Texas, received the **IEEE Medal for Environmental and Safety Technologies** for outstanding accomplishments in the application of technology in the fields of interest to IEEE that improve the environment and/or public safety. The award is sponsored by Toyota Motor Corporation, Japan, and was given to three co-recipients "for developing the lithium-ion battery, which enables significant fuel conservation and reduced emissions as power storage for electric vehicles and for smart grids incorporating renewables."
- **John L. Hennessy**, president, Stanford University, received the **IEEE Medal of Honor**, which is sponsored by the IEEE Foundation. The medal is given for an exceptional contribution or an extraordinary career in IEEE fields of interest. Dr. Hennessy was honored "for pioneering the RISC processor architecture and for leadership in computer engineering and higher education."
- **Leonard Kleinrock**, Distinguished Professor, Computer Science Department, University of California, Los Angeles, received the **IEEE Alexander Graham Bell Medal** "for pioneering contributions to modeling, analysis, and design of packet switching networks." The award, sponsored by Bell Labs, is given for exceptional contributions to the advancement of communications sciences and engineering.
- **Edward J. McCluskey**, professor of electrical engineering and computer science and director, Center for Reliable Computing, Stanford University, received the **IEEE John Von Neumann Medal** "for fundamental contributions that shaped the design and testing of digital systems." The award, sponsored by IBM Corporation, is give in recognition of outstanding achievements in computer-related science and technology.
- **Edmund O. Schweitzer III**, president, Schweitzer Engineering Laboratories, Inc. received the **IEEE Medal in Power Engineering** "for leadership in revolutionizing the performance of electrical power systems with computer-based protection and control equipment." The award is sponsored by IEEE Industry Applications, Industrial Electronics, Power Electronics, and Power & Energy, and the recipient is chosen for outstanding contributions to the technology associated with the generation, transmission, distribution, application, and utilization of electric power for the betterment of society.
- **Fawwaz Ulaby**, Arthur Thurnau Professor of Electrical Engineering and Computer Science, University of Michigan, received the **IEEE James H. Mulligan, Jr. Education Medal**, which is sponsored by MathWorks, Pearson Education, Inc., National Instruments Foundation, and the IEEE Life Members Committee. The medal is given in recognition of outstanding contributions to education in the fields of interest of IEEE. Dr. Ulaby was cited "for contributions to undergraduate and graduate engineering education through innovative textbooks, dedicated mentoring of students, and inspirational teaching."
- **William L. Whittaker**, Fredkin University Professor, Carnegie Mellon University, was awarded the **IEEE Simon Ramo Medal**,

"for pioneering contributions to mobile autonomous robotics, field applications of robotics, and systems engineering." The medal, sponsored by Northrop Grumman Corporation, is awarded to an individual for exceptional achievement in systems engineering and systems science.

- **Savio L-Y. Woo**, Distinguished University Professor and director, Musculoskeletal Research Center, Department of Bioengineering, Swanson School of Engineering, University of Pittsburgh, was awarded the **IEEE Medal for Innovations in Healthcare Technology** "for pivotal contributions to biomechanics and its application to orthopedic surgery and sports medicine." The medal is sponsored by the IEEE Engineering in Medicine and Biology Society and is awarded to an individual who has made outstanding contributions and/or innovations in engineering in the fields of medicine, biology, and healthcare technology.

William F. Banholzer, executive vice president and chief technology officer, Dow Chemical Company, has received the **2012 Malcolm E. Pruitt Award** from the Council for Chemical Research (CCR). The award is given to an individual in industry whose efforts demonstrate exceptional contributions to the development of chemistry-related sciences. Dr. Banholzer, who received the award during the 33rd Annual CCR Conference, held May 20–22 in Dearborn, Michigan, was recognized for establishing a variety of initiatives to fund chemical research and development at U.S. universities.

The 2012 Kavli Prize in Nanoscience was awarded to **Mildred S. Dresselhaus**, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology, "for her pioneering contributions to the study of phonons, electron-phonon interactions, and thermal transport in nanostructures." Over a period of more than 50 years, Dr. Dresselhaus has made advances in our understanding of why the properties of nanoscale materials can have very different properties from those of the same materials at larger dimensions. Her early work on carbon fibers and compounds of different chemical species sandwiched between graphite layers, known as graphite intercalation compounds, laid the groundwork for later discoveries related to the famous C60 buckyball, carbon nanotubes, and graphene. Dr. Dresselhaus received the prize for her research into uniform oscillations of elastic arrangements of atoms or molecules called phonons, phonon-electron interactions, and heat conductivity in nanostructures. The prize includes a $1 million cash award.

Dr. Dresselhaus also received the **Fermi Award**, one of the oldest and most prestigious science and technology honors bestowed by the U.S. government. She was honored "for her scientific leadership, her major contributions to science and energy policy, her selfless work in science education and the advancement of diversity in the scientific workplace, and her highly original and impactful research." The award ceremony took place on May 7, 2012.

Cato T. Laurencin, University Professor and Albert & Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery, University of Connecticut Health Center, has been recognized by *National Geographic* in a special issue of its magazine devoted to "100 Scientific Discoveries That Changed the World." Dr. Laurencin, who is also chief executive officer of the Connecticut Institute for Clinical and Translational Science, was cited for research breakthroughs that could revolutionize the treatment of a torn anterior cruciate ligament (ACL), a common knee injury. He developed a new approach to ACL regeneration using a biocompatible, degradable synthetic braided scaffold that would be surgically implanted to stabilize the knee and facilitate the creation of ligament tissue.

Kuo-Nan Liou, Distinguished Professor of Atmospheric Sciences and Director of the Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, received the **Quadrennial Gold Medal Award** from the International Radiation Commission (IRC), which was founded in 1896 under the auspices of the International Union of Geodesy and Geophysics (IUGG). The award was presented at the 2012 IRC Symposium in Berlin, Germany, on August 8, 2012. Dr. Liou was cited for his "contributions of lasting significance to the field of radiation research."

The Association for Computing Machinery (ACM) presented the **Distinguished Service Award** to **Wm. A. Wulf**, NAE President Emeritus, and former University Professor and AT&T Professor of Engineering and Applied Sciences, Department of Computer Science, University of Virginia, for distinguished service as a leader of the National Science Foundation (NSF) Computer and Information Science and Engineering (CISE) Directorate and as president of NAE. Dr. Wulf helped develop the High Performance Computing and Communication Initiative to advance the construction of a national information infrastructure, and at NSF he oversaw the merger and conversion of ARPANET (Advanced Research Projects Agency Network) from the U.S. Department of Defense to the National Research and Education Network (NREN), a critical step in the evolution of the Internet. At NAE, he oversaw the publication of two influential reports urging educators to prepare for the future of engineering in a global environment. He also promoted NAE's campaign to improve technology literacy and to introduce engineering concepts in K–12 education. In addition, he created the Center on Engineering, Ethics, and Society (CEES) at NAE to raise the profile of engineering ethics and the impacts of engineering on society.

NAE Welcomes Frazier Benya

Frazier Benya

Frazier Benya, who joined the NAE Program Office last October as a program officer for the Center for Engineering, Ethics, and Society (CEES), works with Rachelle Hollander and Simil Raghavan on CEES projects and on the NAE Online Ethics Center website (*onlineethics.org*). Her work has focused on two CEES programs in particular, the Partnership for Education on Climate Change, Engineered Systems, and Society, and Energy Ethics in Science and Engineering Education. Frazier is also assisting in the production of a National Research Council consensus report, *Ethical and Societal Issues in National Security Applications of Emerging Technologies*.

Outside of NAE, Frazier has been working on her Ph.D. at the University of Minnesota (UMN) in the History of Science, Technology and Medicine Program. The focus of her research is the history of bioethics and scientific social responsibility during the 1960s and 1970s. She plans to defend her thesis in October of this year. She also earned an M.A. in bioethics from UMN, for which she analyzed different types of research on the social implications of science and the methodologies of integrating scientific research with ethics research in the United States and Canada. As a graduate student at UMN, she worked on two research projects, one on the history of chronobiology, the study of naturally occurring rhythms in biology and medicine from 1960 to 1990, and the other in the Center for Bioethics on creating a bioethics resource website, *EthicShare.org*, a single index that includes literature relevant to bioethics from a variety of databases. She earned a B.A. from the University of Puget Sound in Science, Technology, and Society.

Center for Engineering, Ethics, and Society/Online Ethics Center Activities

The NAE Center for Engineering, Ethics, and Society and its Online Ethics Center are pleased to announce the launch of the **Energy Ethics Video Challenge** and the **National Institute on Energy, Ethics, and Society**. Both activities are supported by a grant from the National Science Foundation.

The Energy Ethics Video Challenge invites individual students or teams to prepare and submit a short video that examines the ethical aspects of a topic that is important for the nation's energy future and identifies potential approaches to address the issue. Winning videos will be chosen in the following categories: Best Video Award, Theme Awards, and People's Choice Award. Details on the challenge are posted at *www.OnlineEthics.org/Projects/VideoChallenge.aspx*. The deadline for submissions is November 30, 2012.

The National Institute on Energy, Ethics, and Society (NIEES) is a week-long educational seminar for about 20 graduate students or postdoctoral fellows doing energy-related research, to train them for leadership in the fields of energy ethics and energy ethics education.

Students will examine ethical and societal issues associated with U.S. energy choices through lectures and discussions, individual and group projects, and visits to energy research facilities to talk with researchers and managers about the directions and ethical aspects of their work. Students will also develop plans for continuing activities on energy ethics at their home institution. Faculty will include well-known energy scientists, engineers, policymakers, and social scientists and ethicists. The institute is sponsored by NAE and Arizona State University and will be held at the ASU campus in Tempe April 7–13, 2013. Stipends and travel support will be available for five to ten applicants from U.S. programs. Guidelines for applications are available at *http://onlineethics.org/Projects/EESE/26334.aspx*. The deadline for applying is October 31, 2012.

We hope you will encourage students to apply to the Institute and to participate in the video challenge, whether as an independent project or a class assignment.

Grand Challenges Scholars Program

The NAE recently posted an announcement on its website congratulating the third graduating class of the Grand Challenges Scholars Program (GCSP), and NAE President Charles Vest sent each graduate a letter welcoming him or her to the growing number of engineers who have made a dramatic commitment to advancing our civilization.

The GCSP is an offshoot of NAE's Grand Challenges for Engineering, which are based on a consensus of findings by an international committee of leading technological thinkers on achievable, sustainable engineering opportunities for helping people thrive around the globe.

In 2009, leaders from the Pratt School of Engineering at Duke University, the Franklin W. Olin College of Engineering, and the Viterbi School of Engineering at the University of Southern California proposed a model design for a GCSP that includes research experience, an interdisciplinary curriculum (called Engineering +), a global dimension, entrepreneurship, and service learning to provide students with the skills to tackle urgent global challenges in the century to come. Each student pursues an engineering degree focused on one of the 14 Grand Challenges.

Katherine Elfer, a 2012 graduate of Louisiana Tech, received a degree in nanosystems engineering (the first such undergraduate program in the United States), with a concentration in biomedical engineering. Her focus was on the Grand Challenge to "Engineer Better Medicines." As part of a National Science Foundation (NSF) Supervised Undergraduate Research Experience, she worked on the development of smart bandages that contain bioactive materials. Her senior design project, based on that research, was to develop an automated, programmable device to produce the smart bandages. Katherine received an NSF Graduate Fellowship as a result of her in-depth work and will be pursuing her Ph.D. in Biomedical Engineering at Tulane University this fall.

Andrew Sun, who graduated with a degree in mechanical engineering from Duke this year, chose to address the Grand Challenge "Provide Access to Clean Water" by redesigning the India Mark II/III water hand pump currently used in developing communities around the world. The research, entrepreneurship, and service learning components of Andrew's program were based on his work with Engineers Without Borders from August 2008 to January 2012. During this time, he traveled to Uganda with the team and assisted them in refining their technical design for water sustainability. Andrew is pursuing his long-term goal of developing and financing his own company, Aswanet, Ltd., based in Kampala, Uganda, to improve water and sanitation coverage in rural areas of the country.

Since the launch of the GCSP in 2009, 12 universities have joined the program to prepare and educate students, like Katherine and Andrew, who are dedicated to improving the prosperity, security, and quality of life for all people. The vision for GCSP is to attract more colleges and universities and ultimately to spread throughout the nation. It is anticipated that each participating institution will develop its own realization of the five components. Students who complete the program successfully receive the title of Grand Challenge Scholar, which is endorsed by their institutions and NAE.

For more information, visit *www.grandchallengescholars.org/*.

Anderson-Commonweal Interns Join Program Office

Safoah Agyemang

Abby Estabillo

SAFOAH AGYEMANG is in the midst of her third Anderson-Commonweal Internship at NAE. Under the guidance of Catherine Didion, she is working on the NAE Diversity of the Engineering Workforce (DEW) Program and with the National Research Council Committee on Women in Science, Engineering, and Medicine (CWSEM). She has also worked on "Seeking Solutions: Maximizing American Talent by Advancing Women of Color in Academia," a conference held in June 2012, and on the NAE Project on Capitalizing on the Diversity of the Industrial Workforce in Science and Engineering.

Safoah is a junior majoring in biology at Mount St. Mary's University in Emmitsburg, Maryland. When she graduates, she hopes to go on to medical school and eventually to become an obstetrician/gynecologist. She is vice president of campus activities for Women in Science at her school and a member of the Tri-Beta Honor Society (Biology Honors Society).

ABBY ESTABILLO is a first-year intern in the Anderson-Commonweal Internship Program at the National Academies. She is working with Simil Raghavan on the NAE Diversity of the Engineering Workforce (DEW) Program. Specifically, Abby is conducting research for the revised *EngineerGirl!* website, to be launched in the fall of 2012. Last summer, she was a Commonweal intern at the Commonwealth Foundation.

Abby is a sophomore majoring in electrical engineering at Montgomery College in Rockville, Maryland. Next year, she plans to transfer to an accredited four-year university that offers an engineering program. Abby is also an active member of a local Filipino church community in Rockville and has been playing the guitar for five years for the music ministry. During her school year, Abby will return to Commonweal Foundation to work as a part-time office assistant.

NAE 1964–2014: Celebrating 50 Years of Engineering Leadership and Service

50th Anniversary Fundraising Update

NAE's four-year 50th Anniversary fundraising effort is off to a strong start toward meeting its ***50 for the 50th* goals** by December 2014:

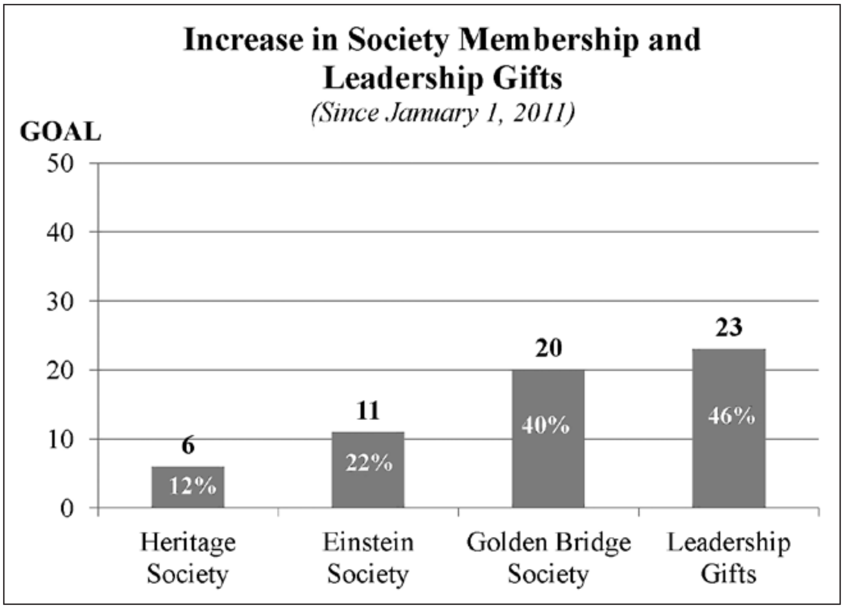
- 50 new members of our lifetime giving societies. The **Einstein Society** honors those who have given $100,000 or more. The **Golden Bridge Society** honors those who have given between $20,000 and $99,999. The **Heritage** Society honors those who have made a planned gift.
- 50 new **Leadership Gifts** of $50,000 or more from corporations, foundations, or individuals.
- 50 percent **participation** by our members.

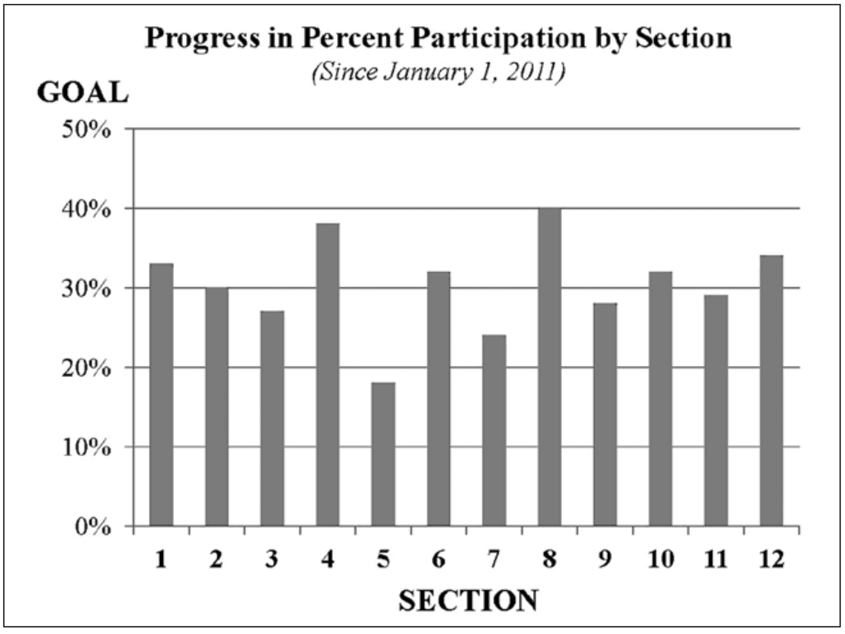
Here is where we stand. (See charts at right.)

NAE is advisor to the nation on matters of engineering and technology and a leader in educating the public about how innovation in engineering supports the U.S. economy, reinforces our national security, and enriches our quality of life. As we approach our 50th year, NAE is asking for your help to spread our message to students of all ages, teachers and professors, the general public, academic and industry leaders, and policymakers.

Thanks to many of our members and friends, we have made impressive steps toward reaching our ambitious goals, but there is still much progress to be made to secure NAE's standing as a national voice for engineering. We hope we can count on your help to achieve our 50th Anniversary goals and position NAE to thrive for the next 50 years and beyond. Please consider making a 50th Anniversary gift to NAE today.

Visit our website at *www.nae.edu/50thgiving* to learn more, or contact Radka Nebesky, Director of Development, at 202.334.3417 or RNebesky@nae.edu.





NAE Annual Meeting, September 30–October 1, 2012

The NAE Annual Meeting will take place **September 30–October 1, 2012**, in the restored NAS Building on Constitution Avenue in Washington, D.C. Members of the NAE Class of 2012 will meet on Saturday, September 29, for an orientation and are then invited, together with the foreign associates, to attend a black tie dinner in their honor hosted by the NAE Council.

The induction ceremony for the Class of 2012 will be held at noon on Sunday, September 30, followed by an awards program.

On Monday morning, October 1, all members and foreign associates are encouraged to attend the Business Session and then the Forum on **Educating Engineers: Preparing 21st Century Leaders in the Context of New Modes of Learning**. President Vest envisions this event as an opportunity to establish a new direction for engineering education in the 21st century.

Section meetings will take place Monday afternoon at the NAS Building and Keck Center. The Annual Meeting will conclude with an optional dinner dance at the JW Marriott.

The brochure, registration, and other information for the NAE 2012 Annual Meeting are available on the NAE website: *www.nae.edu*.

Calendar of Events

September 28–29	NAE Council Meeting
September 29	NAE Peer Committee Meetings
September 30–October 1	NAE Annual Meeting
October 1	Official launch of new *EngineerGirl!* website
October 3	Workshop on Sensing Emerging Conflicts United States Institute of Peace, Washington, D.C.
October 14–17	Frontiers of Engineering Education Irvine, California
October 18–19	Workshop on Operations System Engineering and Peacebuilding
October 29–31	Japan-America Frontiers of Engineering Irvine, California
November 5	Planning Meeting on Incorporating Human-Systems Integration into Engineering Education
November 8–10	*EngineerGirl!* website outreach and exhibit at the Society of Women Engineers 2012 Conference Houston, Texas
November 15–16	Committee on Integrated STEM Education
November 19–20	Committee on Women in Science, Engineering, and Medicine Meeting
December 3–4	Committee on Membership Meeting
December 12	Workshop on Practical Guidance on Science and Engineering Ethics Education for Instructors and Administrators

In Memoriam

JEFFREY S. BECK, 49, Global Polyethylene Marketing Manager, ExxonMobil Chemical Company, died on April 7, 2012. Dr. Beck was elected to NAE in 2011 "for discovery and commercialization of selective, environmentally beneficial catalytic routes to major petrochemicals and for leadership in industrial engineering."

MICHEL BOUDART, 87, William M. Keck Senior Professor of Chemical Engineering, Emeritus, Department of Chemical Engineering, Stanford University, died on May 2, 2012. Dr. Boudart was elected to NAE in 1979 "for contributions to structure, catalysis and chemical reactions surfaces."

DAVID BROWN, 95, retired vice chairman, Halcon International, Inc., died on May 3, 2012. Mr. Brown was elected to NAE in 1978 "for contributions to petrochemical processing technology, engineering literature, and engineering education."

JAMES R. BURNETT, 86, retired executive vice president, TRW Inc., died on April 8, 2012. Dr. Burnett was elected to NAE in 1975 "for contributions in guidance and control for space systems and in the engineering development of U.S. strategic weapon systems."

KARL P. COHEN, 99, retired chief scientist, Nuclear Energy Group, General Electric Company, died on April 6, 2012. Dr. Cohen was elected to NAE in 1967 "for technology of isotope separation and reactor development."

GERALD P. DINNEEN, 87, retired vice president, Science and Technology, Honeywell Inc., died on May 30, 2012. Dr. Dinneen was elected to NAE in 1975 "for contributions to the design of digital computer and satellite communications systems."

L.K. DORAISWAMY, 85, Anson Marston Distinguished Professor in Engineering Emeritus, Department of Chemical and Biological Engineering, Iowa State University, died on June 2, 2012. Dr. Doraiswamy was elected a foreign associate of NAE in 2010 "for outstanding leadership in the development of the Indian chemical industry and contributions to organic synthesis engineering, heterogeneous reactions, and reactors."

DANIEL J. FINK, 85, president, D.J. Fink Associates, Inc., died on June 1, 2012. Mr. Fink was elected to NAE in 1974 "for contributions to aeronautics and space in government and in private industry."

DONALD W. GENTRY, 69, consultant, died on July 2, 2012. Dr. Gentry was elected to NAE in 1996 "for contributions to understanding rock mass responses in long-wall coal mining, improvements in mining education, professional development, and public service."

JAMES N. GRAY, 68, Technical Fellow, Microsoft Corporation, died on January 28, 2012. Dr. Gray was elected to NAE in 1995 "for contributions to the development and understanding of database systems, especially concurrent and distributed systems."

ANDREW R. HILEMAN, 85, retired advisory engineer, Westinghouse Electric Corporation, and consultant, died on February 3, 2012. Mr. Hileman was elected to NAE in 1999 "for contributions to the understanding of lightning and its effects on electric power system performance."

SHELDON E. ISAKOFF, 86, retired director, Engineering R&D Division, E.I. du Pont de Nemours & Company, died on January 29, 2012. Dr. Isakoff was elected to NAE in 1980 "for leadership in industrial chemical engineering research, especially in the control of unsteady state operations."

THEODORE C. KENNEDY, 81, retired, co-founder of BE&K, Inc., died on May 8, 2012. Mr. Kennedy was elected to NAE in 1999 "for leadership and innovation in advancing the nation's construction industry."

JOHN LOWE III, 95, retired consulting engineer, died on January 2, 2012. Mr. Lowe was elected to NAE in 1974 "for leadership in the development and application of the principles of soil mechanics."

DOUGLAS C. MOORHOUSE, 86, Chairman Emeritus, Woodward-Clyde Group, Inc., died on March 14, 2012. Mr. Moorhouse was elected to NAE in 1982 "for innovative technical and managerial leadership in geotechnical engineering, earth sciences, and environmental systems in response to the needs of society."

EDWARD W. PRICE, 91, Regents' Professor Emeritus, School of Aerospace Engineering, Georgia Institute of Technology, died on June 11, 2012. Mr. Price was elected to NAE in 2000 "for critical contributions to the understanding of solid propellant combustion and solid rockets developments."

ADRIAN W. ROTH, 90, honorary member and past vice president, Academy of Technical Sciences of Switzerland, died on February 29, 2012. Dr. Roth was elected a foreign associate of NAE in 1990 "for the development of circuit breakers and sulphur hexafluoride insulated substations, which were vital advancements of power systems."

MAURICE E. SHANK, 90, retired vice president, Pratt & Whitney of China, Inc., died on February 21, 2012. Dr. Shank was elected to NAE in 1983 "for outstanding contributions and technical direction in advancing the state of the art in aircraft gas turbine technology."

ARTHUR M. SQUIRES, 96, University Distinguished Professor Emeritus, Virginia Polytechnic Institute and State University, died on May 18, 2012. Dr. Squires was elected to NAE in 1977 "for contributions to the research and understanding of coal gasification and the recovery of organic chemicals from coal."

BENO STERNLICHT, 84, president, Benjosh Management Corporation, died on May 6, 2012. Dr. Sternlicht was elected to NAE in 1980 "for pioneering new turbomachinery development, energy recovery systems and propulsion systems, including the world's first Brayton cycle closed-loop gas-bearing turbomachinery."

CHARLES E. TREANOR, 87, retired vice president and chief scientist, Calspan Corporation, and consultant, died on May 27, 2012. Dr. Treanor was elected a foreign associate of NAE in 1990 "for contributions to the physics of high-temperature gases, hypersonic flight, and flow lasers and for innovative research management."

HOWARD S. TURNER, 100, retired chairman, Turner Construction Company, died on April 25, 2012. Dr. Turner was elected to NAE in 1973 "for contributions to the technology of coal slurry pipelining, carbonizing coal by fluidization, and basic oxygen steel making."

JOSEPH E. WARREN, 85, director, Frontier Resources International, PLC, died on June 16, 2012. Dr. Warren was elected to NAE in 1993 "for contributions to development of fractured reservoir mechanics and application of economic risk analysis."

PAUL A. WITHERSPOON, 93, Professor Emeritus of Geological Engineering, University of California, Berkeley, and retired Faculty Senior Scientist, Lawrence Berkeley National Laboratory, died on February 10, 2012. Dr. Witherspoon was elected to NAE in 1989 "for pioneering achievements in geothermal energy, underground storage, hydrogeology, and the flow of fluids in fractured and porous rocks."

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council (NRC). Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Keck 360, Washington, D.C. 20001. For more information or to place an order, contact NAP online at *www.nap.edu* or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Challenges in Characterizing Small Particles: Exploring Particles from the Nano- to Microscales. A lack of understanding about the properties and chemical composition of small particles, which are ubiquitous in both the natural and built environments, limits our ability to predict and control their applications and impacts. This National Research Council report provides summaries of presentations and discussions at a 2010 National Academies roundtable, where speakers discussed (1) the most important information about small particles in different media, (2) the critical importance of small particles in environmental science, materials and chemical sciences, biological science, and engineering, and (3) the challenges involved in the static, dynamic, experimental, computational, and theoretical characterization of materials at the nanoscale and microscale. The event included several presentations of "research tools" highlighting advances in the characterization of small particles.

NAE member **Mark A. Barteau**, senior vice provost for research and strategic initiatives, University of Delaware, co-chaired the Chemical Sciences Roundtable. NAE members on the Board on Chemical Sciences and Technology were **Pablo G. Debenedetti** (co-chair), Class of 1950 Professor in Engineering and Applied Science, Department of Chemical and Biological Engineering, Princeton University; **David L. Morse**, executive vice president and CTO, Corning Incorporated; and **David R. Walt**, Robinson Professor of Chemistry, Tufts University. Paper, $42.00.

Testing of Body Armor Materials: Phase III. Since 2009, several reviews have been released by the General Accountability Office and others of how body armor worn by the military and personnel in other departments is tested. The U.S. Department of Defense Director, Operational Test and Evaluation, requested that the NRC Division on Engineering and Physical Sciences conduct a three-phase study to investigate issues raised in these reviews. Phases I and II resulted in two NRC letter reports: one in 2009 and one in 2010. The present volume, Phase III, provides a road map for reducing the variability of clay processing, suggests new materials and processes for the future, and discusses how statistics might be used to develop a more scientific determination of sample sizes for body armor testing. In addition, this report committee develops ideas for revising or replacing the Prather study methodology and reviews methodologies and technical approaches to the testing of military helmets. The committee also explores the feasibility of combining various national body armor testing standards.

NAE members on the study committee were **Thomas F. Budinger**, Professor of the Graduate School, University of California, Berkeley, E.O. Lawrence Berkeley National Laboratory; **Morton M. Denn**, Albert Einstein Professor of Science and Engineering, City College of New York (CUNY), The Benjamin Levich Institute; and **Sheldon M. Wiederhorn**, Senior NIST Fellow Emeritus, National Institute of Standards and Technology. Paper, $65.00.

Review of the 21st Century Truck Partnership, Second Report. In July 2010, the National Research Council (NRC) appointed the Committee to Review the 21st Century Truck Partnership (21CTP), Phase 2, to conduct an independent review of the program. 21CTP is a cooperative research and development partnership that includes four federal agencies—the Department of Energy, Department of Transportation, Department of Defense, and Environmental Protection Agency—and 15 industry partners. The purpose of the program is to reduce fuel consumption and emissions, improve the safety of heavy-duty vehicles, and support research, development, and demonstration for commercially viable products and systems. This second report includes a review of the 21CTP as a whole, major areas of focus, management and the setting of priorities, efficiency of operations, and the new SuperTruck program.

NAE members on the study committee were **Joseph M. Colucci**, president, Automotive Fuels Consulting Inc., and retired executive director, materials research, General Motors Research and Development; **John G. Kassakian**, professor of electrical engineering and computer science, Massachusetts Institute of Technology; **Bernard I. Robertson**, retired senior vice president, Engineering Technologies and Regulatory Affairs, and retired general manager, Truck Operations, DaimlerChrysler Corporation; **Kathleen C. Taylor**, retired director, Materials and Processes Laboratory, General Motors Corporation; and **Wallace R. Wade**, retired technical fellow and chief engineer, Ford Motor Company. Paper, $49.00.

Building Hawaii's Innovation Economy: Summary of a Symposium. To encourage growth and employment in an increasingly competitive global economy, many U.S. states and regions have developed programs to attract and grow companies and attract the talent and resources necessary to develop innovation clusters. In addition, a variety of federal agencies have recently launched initiatives to coordinate and concentrate government investments in the development of regional centers of innovation, business incubators, and other strategies to encourage entrepreneurship and high-tech development. This report reviews selected state and regional programs to identify best practices with regard to goals, structures, instruments, modes of operation, synergies among private and public programs, funding mechanisms and levels, evaluation strategies, capitalizing on federal and state investments to address critical national needs, and efforts to strengthen existing industries and new technology focus areas, such as nanotechnology, stem cells, and energy.

NAE member **Mary L. Good**, Dean Emeritus and Special Advisor to the Chancellor for Economic Development, University of Arkansas at Little Rock, and former Under Secretary for Technology, U.S. Department of Commerce, chaired the study committee. Hardcover, $45.00.

Review of the EPA's Economic Analysis of Final Water Quality Standards for Lakes and Flowing Waters in Florida. The Environmental Protection Agency's estimate of costs associated with implementing numeric nutrient criteria in Florida's waterways was significantly lower than many stakeholders expected. The discrepancy was due, in part, to the fact that EPA's analysis included only the incremental cost of reducing nutrients in waters it considered "newly impaired" as a result of new criteria—not the total cost of improving water quality in Florida. The authoring committee of this report found that EPA's cost analysis would have been more accurate if it had described the differences between the new numeric criteria rule and the narrative rule it is meant to replace and explained how the differences affect the costs of implementing nutrient reductions over time instead of at a fixed point in time. Such an analysis would also have more accurately described which sources of pollutants (e.g., municipal wastewater treatment plants or agricultural operations) would bear the costs over time under the different rules and would have clarified uncertainties in cost estimates.

NAE member **Glen T. Daigger**, senior vice president and chief technology officer, CH2M Hill Inc., chaired the study committee. Paper, $42.00.

Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security. This report provides a course of action for ensuring that U.S. research universities continue to produce the knowledge, ideas, and talent the country needs to be a global leader in the 21st century. With an eye toward strengthening and expanding the partnerships among universities and government, business, and philanthropy that have been central to American prosperity and security, this report focuses on the ten most important actions that Congress, the federal government, state governments, research universities, and others could take to strengthen the research and educational missions of research universities, their relationships with other actors in the national research enterprise, and their ability to transfer new knowledge and ideas to those who can use them productively. The report committee describes trends in university financing, prospects for improving university operations, opportunities for deploying technologies, and improvements in the regulation of institutions of higher education. In addition, the committee suggests how pathways to graduate education can be improved, how universities can increase student diversity, and how doctoral education might be realigned to complement the current careers of new doctoral graduates. This volume will be an important resource for policy makers on the federal and state levels, university administrators, philanthropic organizations, faculty, technology transfer specialists, libraries, and researchers.

NAE members on the study committee were **Charles O. Holliday Jr.** (chair), retired chairman of the board and CEO, DuPont; **James J. Duderstadt**, President Emeritus and University Professor of Science and Engineering, University of Michigan; **John L. Hennessy**, president, Stanford University; and **Cherry A. Murray**, dean, School of Engineering and Applied Sciences, Harvard University. Paper, $49.00.

Export Control Challenges Associated with Securing the Homeland. Rather than withdraw from global networks, which would undermine the fabric of global commerce and the free movement of people, the U.S. government, led by the Department of Homeland Security (DHS), is taking the lead in protecting global networks in which the United States participates and that have become vital to the U.S. economy and society. These networks are both real (e.g., civil air transport, international ocean shipping, postal services, international air freight) and virtual (e.g., the Internet, international financial payments systems). The report committee finds that problems have arisen because the current export policy does not take into account the unique mission of DHS relative to export controls. As the committee explains, the U.S. Departments of Defense and State must (1) recognize the international nature of the statutory mission of DHS, (2) develop internal processes at DHS that meet export-control requirements and implement export-control policies, and (3) reform export-control interagency processes to enable DHS to cooperate with its foreign counterparts.

NAE member **C. Kumar N. Patel**, president and CEO, Pranalytica Inc., was a member of the study committee. Paper, $35.00.

Summary of the Workshop to Identify Gaps and Possible Directions for NASA's Micrometeoroid and Orbital Debris Programs. This report provides a summary of a two-day workshop held March 9–10, 2011, during which speakers presented a wide range of perspectives on matters concerning Micrometeoroid and Orbital Debris (MMOD) programs of the National Aeronautics and Space Administration (NASA), including the agency's mission operators and the relationship of NASA's MMOD programs to other federal agencies and commercial industry, and orbital debris retrieval and removal. The authoring committee of this report creates an advisory dialogue on potential opportunities for improving program and maintenance practices as a platform for assessing NASA's existing efforts, policies, and organizations with regard to orbital debris and micrometeoroids.

NAE members on the study committee were **George J. Gleghorn** (vice chair), Retired Vice President and Chief Engineer, TRW Space and Technology Group, and **Kyle T. Alfriend**, TEES Distinguished Research Chair, and professor of aerospace engineering, Texas A&M University. Paper, $15.00.

Analysis of Cancer Risks in Populations near Nuclear Facilities: Phase I. In the late 1980s, the National Cancer Institute initiated an investigation of cancer risks in populations near 52 commercial nuclear power plants and 10 U.S. Department of Energy nuclear facilities (including research and nuclear weapons production facilities and one reprocessing plant) in the United States. The results of the investigation were used as a primary resource for communicating with the public about cancer risks near nuclear facilities. The U.S. Nuclear Regulatory Commission (USNRC) requested that the National Academy of Sciences provide an updated assessment of cancer risks in populations near USNRC-licensed nuclear facilities that use or process uranium for the production of electricity. The focus of this Phase 1 report is on identifying scientifically sound approaches for a new assessment of cancer risks, and the results will be used to inform the design of a cancer-risk assessment, which will be carried out in Phase 2. This report will be of interest to the general public, communities near nuclear facilities, health care providers, policy makers, state and local officials, community leaders, and the media.

NAE member **George M. Hornberger**, director, Vanderbilt Institute for Energy and Environment and Distinguished University Professor, Department of Civil and Environmental Engineering, Vanderbilt University, was a member of the study committee. Paper, $68.00.

Assessing the Reliability of Complex Models: Mathematical and Statistical

Foundations of Verification, Validation, and Uncertainty Quantification. Despite the ubiquity of uncertainties in computational estimates of reality and the necessity of quantifying them, advances in computing hardware and algorithms have dramatically improved computational simulations of complex processes, which can now address questions that in the past could only be addressed by resource-intensive experimentation, if at all. This report includes discussions of changes in the way professionals are educated and information is disseminated that should improve the capability of future practitioners of verification, validation, and uncertainty quantification (VVUQ) to apply VVUQ methodologies to difficult problems, improve the ability of VVUQ customers to understand results and use them to make informed decisions, and improve the way all VVUQ stakeholders communicate with each other. This report is an essential resource for decision and policy makers in the field, students, stakeholders, UQ experts, and VVUQ educators and practitioners.

NAE members on the study committee were **Stephen M. Pollock**, Herrick Emeritus Professor of Manufacturing, University of Michigan, and **Howard A. Stone**, professor, Department of Mechanical and Aerospace Engineering, Princeton University. Paper, $42.00.

Recapturing NASA's Aeronautics Flight Research Capabilities. NASA's contributions to the overall economy and balance of trade of the United States through the sale of aircraft throughout the world have included advanced flight control systems, deicing devices, thrust-vectoring systems, wing fuselage drag reduction configurations, aircraft noise reduction, advanced transonic airfoil and winglet designs, and flight systems. Each of these contributions was first demonstrated in NASA's flight research programs and then flight demonstrations on full-scale aircraft flying in environments identical to those in which the aircraft operate (i.e., flight research). The loss of flight research capabilities at NASA has removed a primary research tool and substantially blocked progress throughout its aeronautics program. In this report, a committee of experts discusses NASA's motivation for pursuing flight research and identifies challenges that can best be addressed through flight research. The report provides three case studies that illustrate the current state of NASA's Aeronautics Research Mission Directorate (ARMD): (1) the Environmentally Responsible Aviation program, (2) the Fundamental Research Program (FRP) hypersonics projects, and (3) FRP supersonics projects. The committee then identifies problems in ARMD organization and management and suggests solutions. The committee concludes that the agency's overall progress in aeronautics is severely constrained by its inability to advance its research projects to the flight research stage, a vital step in bridging the confidence gap. Without a flight research capability, NASA's aeronautics research cannot progress, make new discoveries, or contribute to U.S. aerospace preeminence.

NAE members on the study committee were **Wesley L. Harris** (chair), Charles Stark Draper Professor of Aeronautics and Astronautics and associate provost, Massachusetts Institute of Technology; **Neil A. Armstrong**, Chairman of the Board Emeritus, EDO Corporation; **Ronald F. Probstein**, Ford Professor of Engineering Emeritus, Massachusetts Institute of Technology; and **Eli Reshotko**, Kent H. Smith Professor Emeritus of Engineering, Case Western Reserve University. Paper, $39.00.

Fueling Innovation and Discovery: The Mathematical Sciences in the 21st Century. To function well in a technologically advanced society, every educated person should have a reasonable level of understanding of the mathematical sciences. This report, which describes recent advances in mathematical sciences and advances enabled by research in the field, is geared toward general readers who want to know more about how these advances are changing our understanding of the world, creating new technologies, and transforming industries. Prepared as part of Mathematical Sciences in 2025, a broad-based assessment of the current state of mathematical sciences in the United States, the report describes the contributions of research in the mathematical sciences to our understanding of the universe and the human genome, explores how they contribute to health care and national security, and highlights the importance of mathematical knowledge and training to a variety of industries, such as information technology and entertainment. This report will be useful to policy makers, researchers, business leaders, students, and others interested in learning more about connections between mathematical sciences and our modern world.

NAE members on the study committee were **Thomas E. Everhart** (chair), President Emeritus, California Institute of Technology; **Eva**

Tardos, Jacob Gould Schurman Professor of Computer Science, Cornell University; and **Margaret H. Wright**, Silver Professor of Computer Science, Courant Institute of Mathematical Sciences, New York University. Paper, $19.95.

Computing Research for Sustainability. Information technology (IT) is a natural bridge between technical and social solutions to problems such as sustainability because it can improve communication and transparency and encourage necessary economic, political, and cultural adjustments. Moreover, IT is at the heart of nearly every large-scale socioeconomic system, including systems for finance, manufacturing, and the generation and distribution of energy. The focus of this report can be summed up as "greening through IT," the application of computing to promote sustainability. The goals of the report are twofold: to highlight areas where IT innovation and computer science (CS) research can help and to urge the computing research community to bring CS approaches and methodologies to bear on pressing global challenges. The report committee argues that IT and CS research can have a significant, measurable impact on addressing medium- and long-term challenges. The committee offers findings and recommendations in four areas: (1) the relevance of IT and CS to sustainability; (2) the value of the CS approach to problem solving, particularly as it pertains to sustainability challenges; (3) key CS research areas; and (4) strategic and pragmatic approaches for CS research on sustainability.

NAE members on the study committee were **Deborah L. Estrin** (chair), professor of computer science and Jon Postel Chair in Computer Networks, University of California, Los Angeles; and **David E. Culler**, professor and chair, Computer Science Division, University of California, Berkeley. Paper, $48.00.

Rising Above the Gathering Storm: Developing Regional Innovation Environments–A Workshop Summary. In October 2005, the National Academy of Sciences, National Academy of Engineering, and Institute of Medicine released Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, a call to action. The blue ribbon committee that wrote the report concluded that "the scientific and technological building blocks critical to the United States economic leadership are eroding at a time when many other nations are gathering strength." The committee laid out 20 recommendations and warned that failure to take action could have dire economic consequences. The report sparked intense discussion among policy makers, industry leaders, and the general public. Five years later, a second report, Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5, an assessment of changes in America's competitive posture, concluded that "our nation's outlook has not improved, but rather has worsened" and noted examples of other nations that had done more than the United States to upgrade their investments in education, technological infrastructure, and innovation systems. In September 2011, a major workshop, "Rising Above the Gathering Storm: Developing Regional Innovation Environments," was held in Madison, Wisconsin. The workshop brought together leaders in education, government, economic development, and industrial innovation to discuss state and regional initiatives to boost competitiveness through science, technology, and innovation. The conference was organized around four major themes: Revitalizing K-12 Science and Mathematics Education; Strengthening Undergraduate Education in Science and Engineering; Building Effective Partnerships among Governments, Universities, Companies, and Other Stakeholders; and Fostering Regional Technology Development and Entrepreneurship. The present volume provides a summary that includes an overview of the workshop presentations, observations, and recommendations.

NAE members **Ruth A. David**, president and chief executive officer, ANSER (Analytic Services Inc.); **C.D. (Dan) Mote Jr.**, Regents Professor and Glenn L. Martin Institute Professor of Engineering, University of Maryland; and **William J. Spencer**, Chairman Emeritus, SEMATECH, were members of the workshop planning committee. Paper, $33.00.

An Interim Report on Assuring DOD a Strong Science, Technology, Engineering, and Mathematics (STEM) Workforce. This interim report is part of an 18-month study to assess the science, technology, engineering, and mathematics (STEM) capabilities of the workforce the U.S. Department of Defense (DOD) and U.S. defense industrial base will need to meet national and private goals, objectives, and priorities. The authoring committee discusses whether the current DOD workforce and strategy will meet those needs, identifies and evaluates options, and recommends strategies to help DOD meet its future STEM needs. The study was undertaken by the National Academy of Engineering and the National Research Council to advise the assistant secretary of defense for research and engineering on the fiscal year 2012 planning process and help lay the groundwork for the future. Earlier in the project, on August 1-2, 2011, the study committee and representatives of the U.S. defense industrial base convened a workshop in Rosslyn, Virginia, to gather a wide range of views from public- and private-sector stakeholders in the future STEM workforce, including major defense contractors and nongovernmental organizations. A final report will be released at the conclusion of the study.

NAE members on the study committee were **Norman R. Augustine** (co-chair), retired chairman and CEO, Lockheed Martin Corporation; **C.D. (Dan) Mote Jr.** (co-chair), Regents Professor and Glenn L. Martin Institute Professor of Engineering, University of Maryland; **Mary L. Good**, Dean Emeritus, Special Advisor to the Chancellor for Economic Development, University of Arkansas at Little Rock, and former under secretary for technology, U.S. Department of Commerce; **Robert J. Hermann**, private consultant, Bloomfield, Connecticut; **Anita K. Jones**, University Professor Emerita, School of Engineering and Applied Science, University of Virginia; **Frances S. Ligler**, U.S. Navy Senior Scientist, Center for Bio/Molecular Science & Engineering, Naval Research Laboratory; **Paul D. Nielsen**, director and CEO, Software Engineering Institute, and retired Major General, USAF; **C. Kumar N. Patel**, president and CEO, Pranalytica Inc.; and **Stephen M. Robinson**, Professor Emeritus, University of Wisconsin-Madison. Free PDF.

Improving the Decision Making Abilities of Small Unit Leaders. For the past decade, the U.S. Marine Corps and its sister services have been engaged in "hybrid warfare," which includes active combat and civilian support. Hybrid warfare typically occurs in environments characterized by conventional weapons, irregular tactics, terrorism, disruptive technologies, and criminality to destabilize an existing order. In August 2010, the National Research Council established the Committee on Improving the Decision Making Abilities of Small Unit Leaders to examine the operational environment, existing abilities, and gaps in data, technology, skill sets, training, and measures of effectiveness for enhanced company operations in hybrid, complex environments. The authoring committee recommends operational and technical approaches for improving the decision making abilities of small unit leaders, including acquisitions and experimentation that might be undertaken by the Marine Corps and/or others specifically to improve such decision making. The goal is to ease the burden on small unit leaders and prepare them for success. The committee also identifies a responsible organization to ensure that training and education programs are properly developed, staffed, operated, evaluated, and expanded.

NAE member **Alan R. Washburn**, Distinguished Professor of Operations Research, U.S. Naval Postgraduate School, was a member of the study committee. Paper, $42.00.

NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space. The National Aeronautics and Space Administration's (NASA's) Office of the Chief Technologist (OCT) has begun to rebuild the agency's advanced space technology program with plans laid out in 14 draft technology roadmaps. It has been years since NASA had a vigorous, broad-based program in advanced space technology development, and its technology base has been largely depleted in the interim. Success in future NASA space missions will depend on advanced technology developments that should already be under way. A committee of experts from around the country, including from the external technical community, was convened to consider the 14 draft technology roadmaps prepared by OCT and to rank the top technical challenges and highest-priority technologies that NASA should emphasize in the next five years. This report provides specific guidance and recommendations on how the effectiveness of the technology development program managed by OCT can be enhanced in the face of scarce resources.

NAE members on the study committee were **John D. Anderson Jr.**, curator of aerodynamics, Aeronautics Division, National Air and Space Museum, Smithsonian Institution; **Edward F. Crawley**, Ford Professor of Engineering and director, Bernard M. Gordon–MIT Engineering Leadership Program, Massachusetts Institute of Technology; and **Lester L. Lyles**, independent consultant, Vienna, Virginia. Paper, $38.00.

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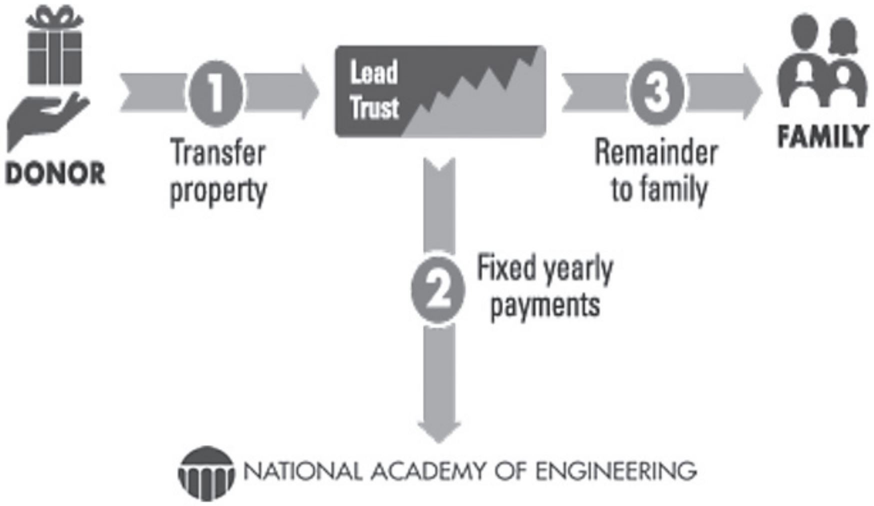

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